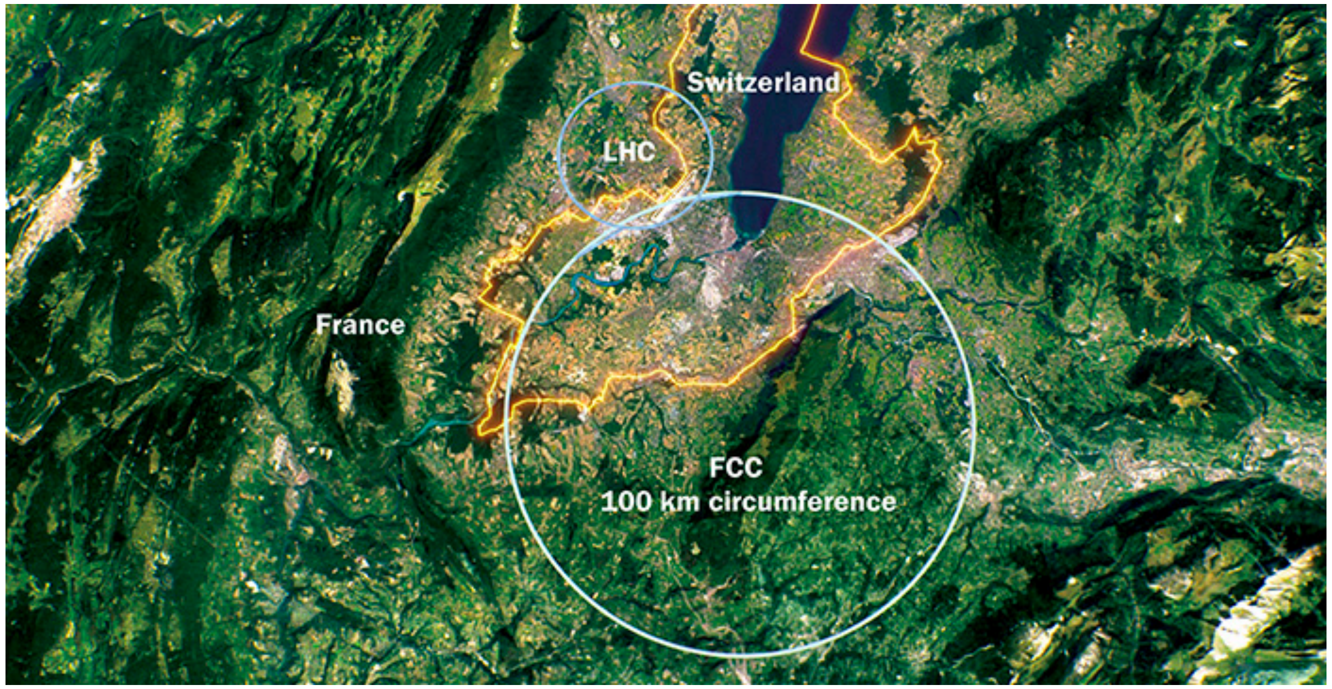
Open Questions and New Ideas on Hadron Colliders



Heather M. Gray, UC Berkeley/LBNL, 20 July 2020

Open Questions for the Energy Frontier

…and beyond

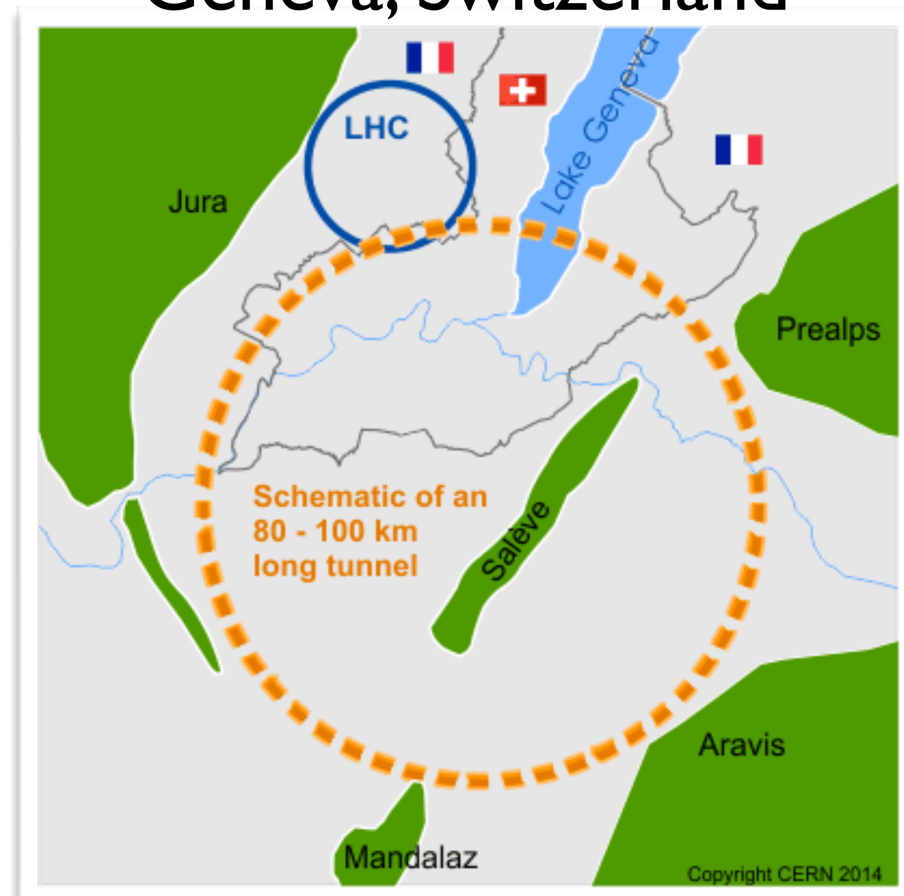
- Unexplained experimental evidence
  - Nature of dark matter
  - Origin of the matter-antimatter asymmetry
  - Existence and hierarchy of neutrino masses
- Problems and puzzles
  - EW hierarchy problem or why is the Higgs boson so light?
  - Strong CP problem or why is theta so small?
  - Flavor puzzle or why are there three generations or quarks and leptons?

(Hadron) colliders have the potential to probe each these!

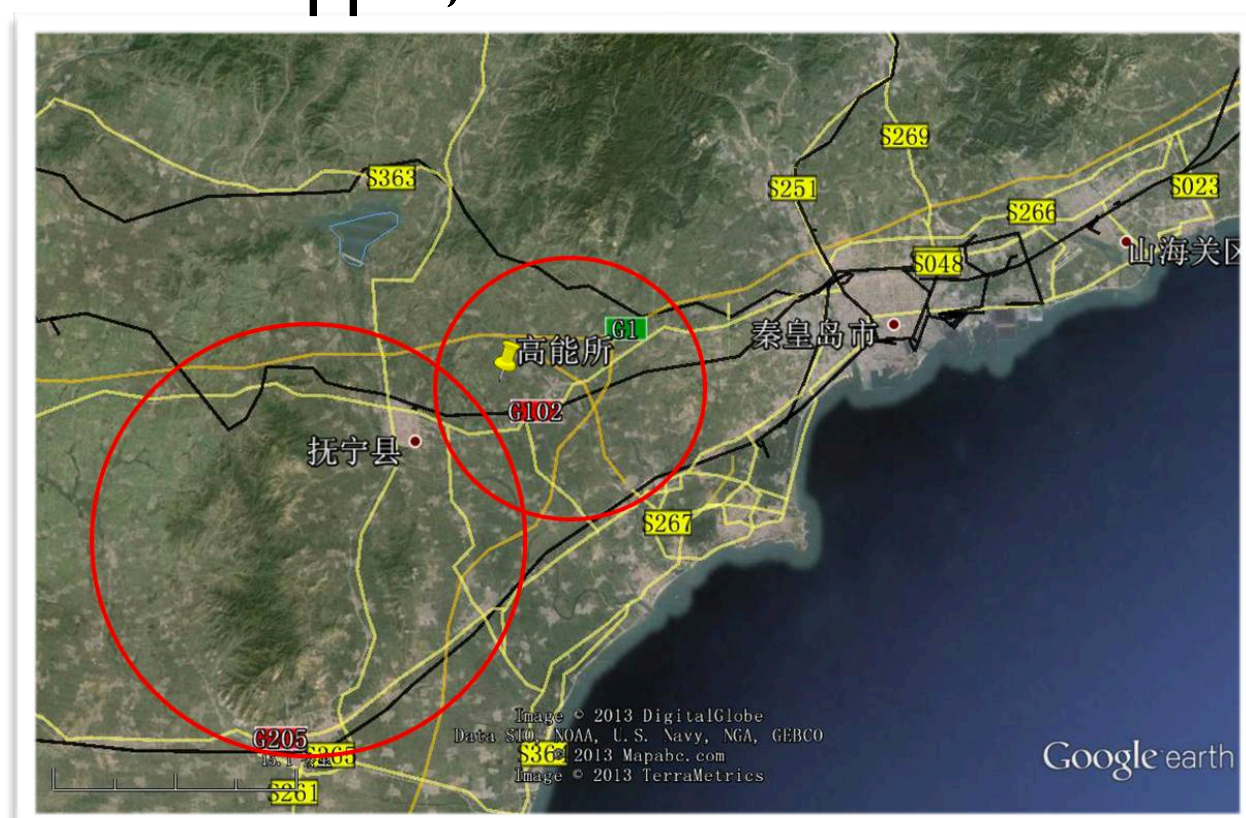
Future Hadron Colliders

- Future hadron colliders that have been considered
  - High-luminosity LHC (**HL-LHC**)
  - High-energy LHC (**HE-LHC**)/Low-energy FCC (**LE-FCC**)
  - Future Circular Collider (**FCC-hh**)
  - Super Proton-Proton Collider (**SppC**)
- Other colliders, not covered here
  - e+e- colliders (Peskin, Robson, Klute, Q+Ruan)
  - LHeC/FCC-eh (Armesto)
  - Muon colliders (Lucchesi)
  - FCC-HI, heavy-ion physics
  - Flavour physics

Geneva, Switzerland

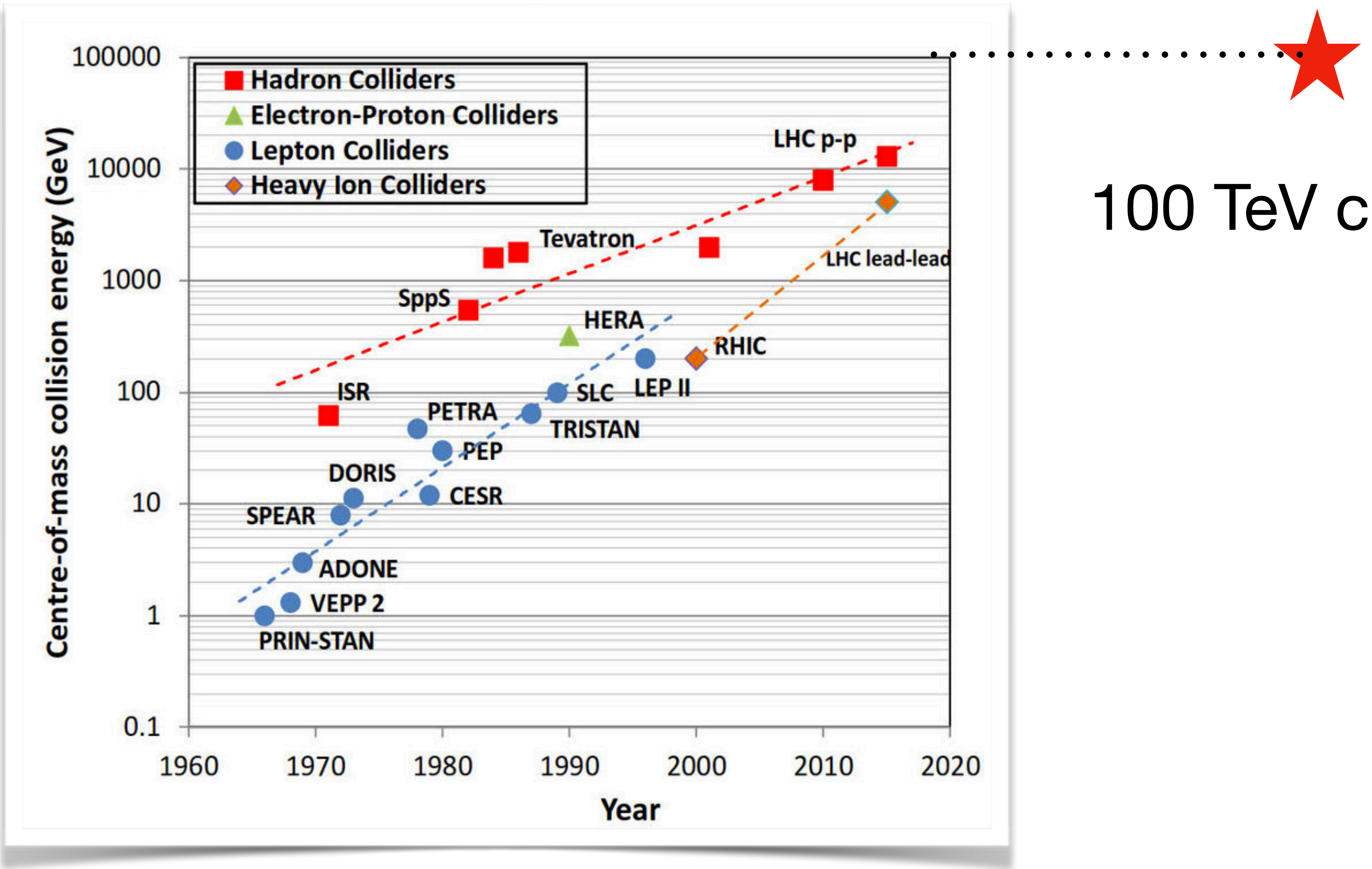


SppC, various sites in China



Why hadron colliders?

- Historically and in general pp colliders allow us to reach the **highest possible energy**
  - Large mass/energy reach in powerful searches for **new physics**
- However, as we've learnt from first the Tevatron and then the LHC, they are also capable of **precision physics measurements** despite the larger backgrounds compared to electron-positron colliders



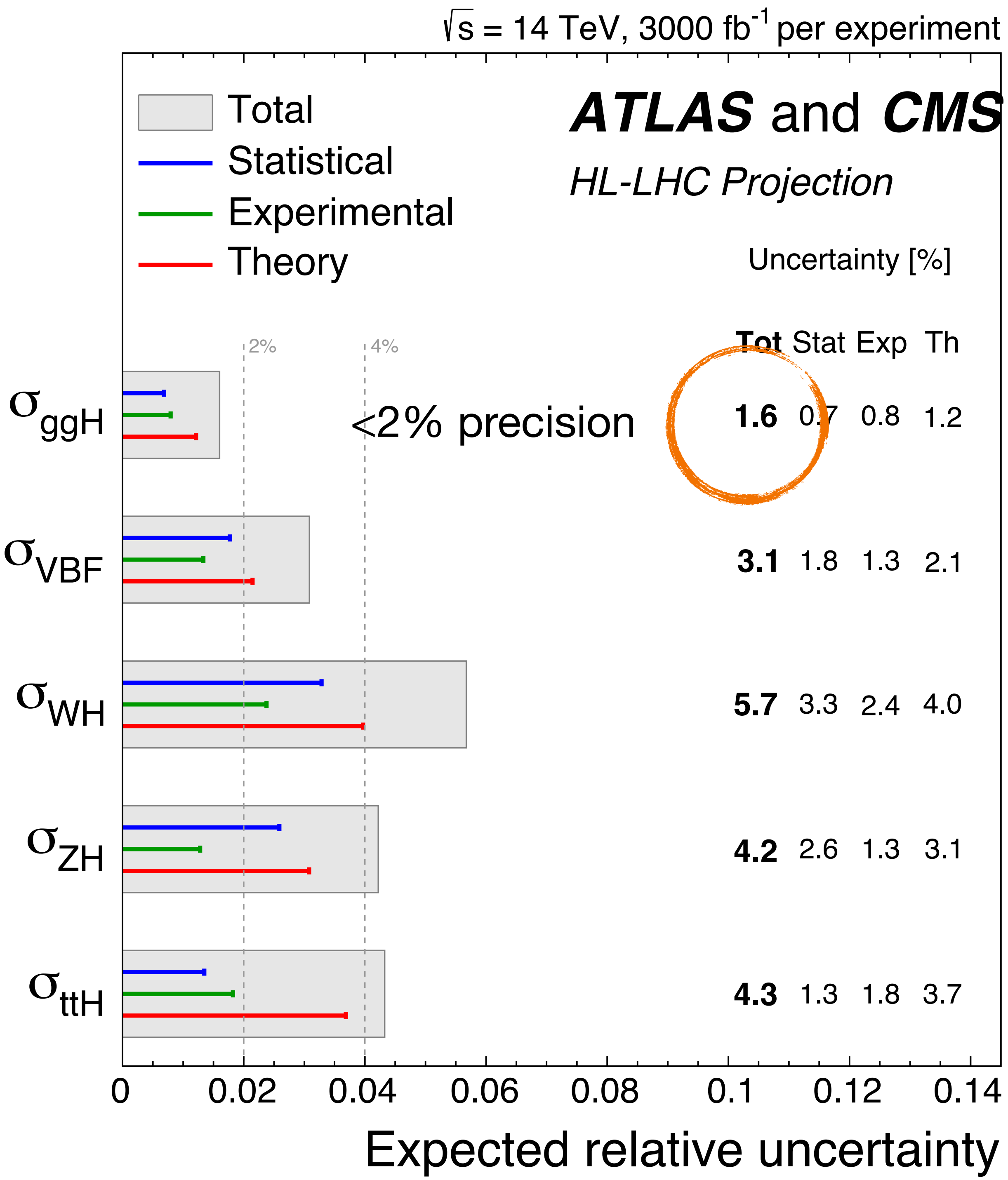
100 TeV collider

Precision Measurements

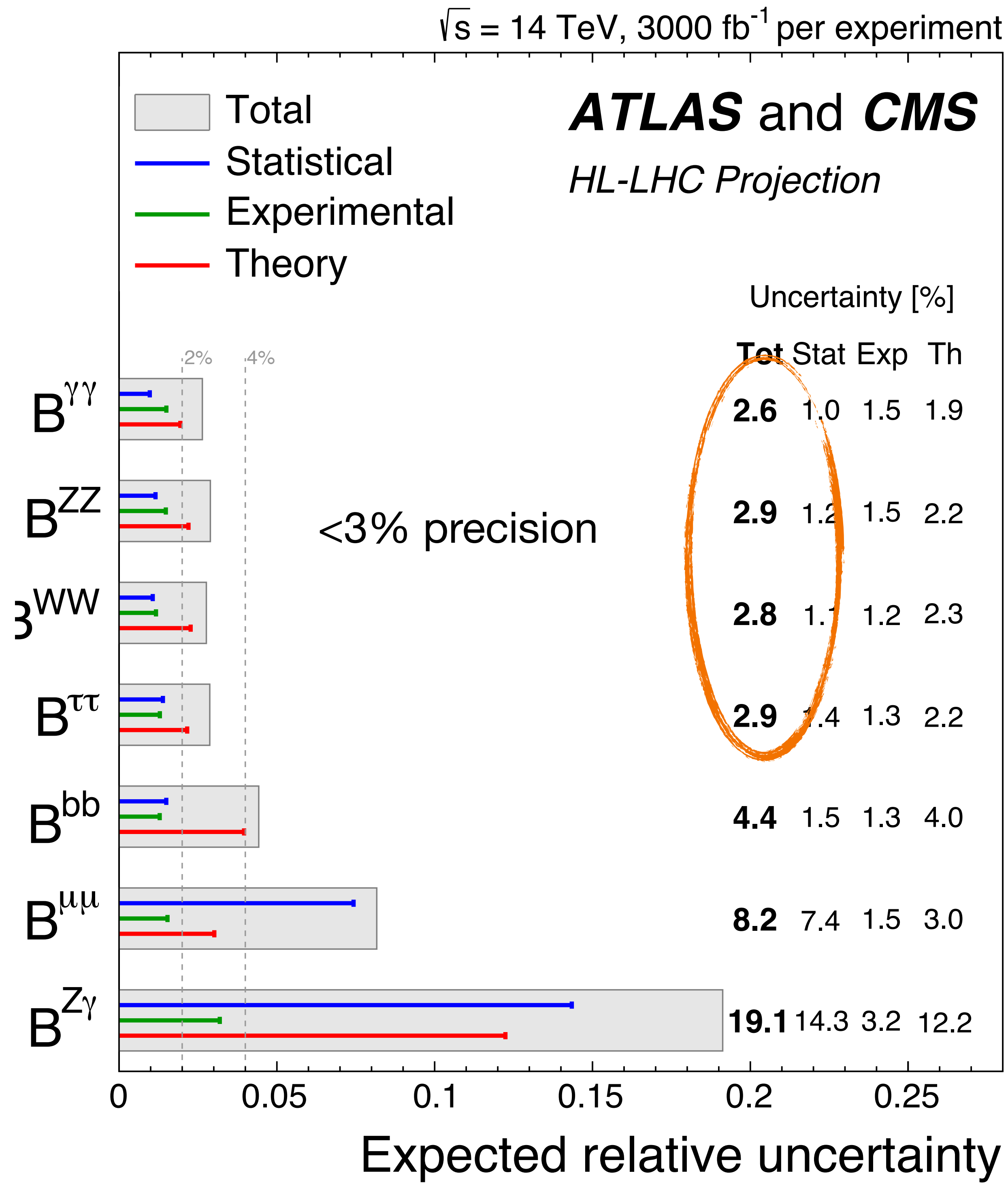
Questions relating to the Higgs boson will be clear target for any future collider due to its close connection with many open questions

Higgs Boson couplings at the HL-LHC

Production



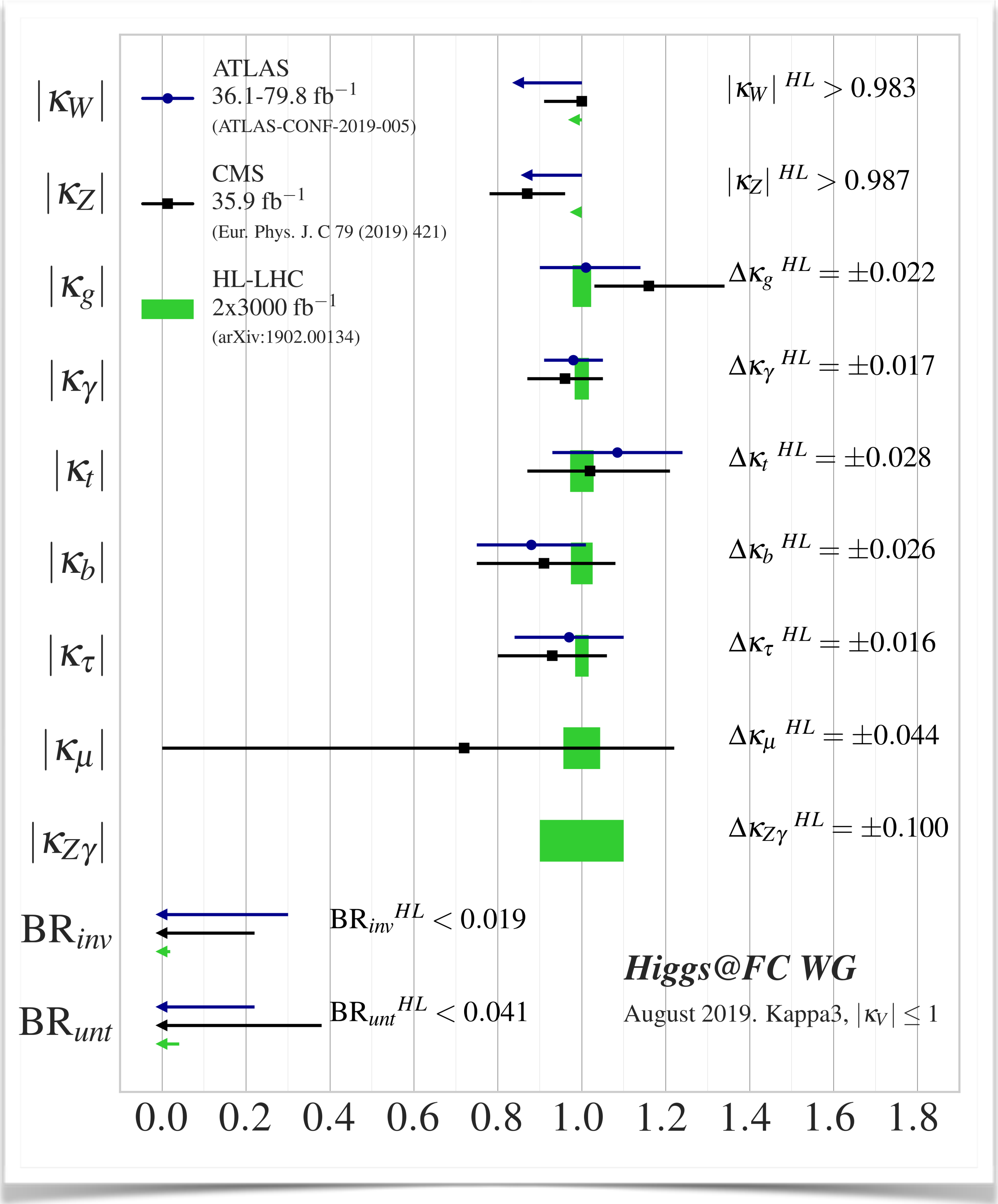
Decays



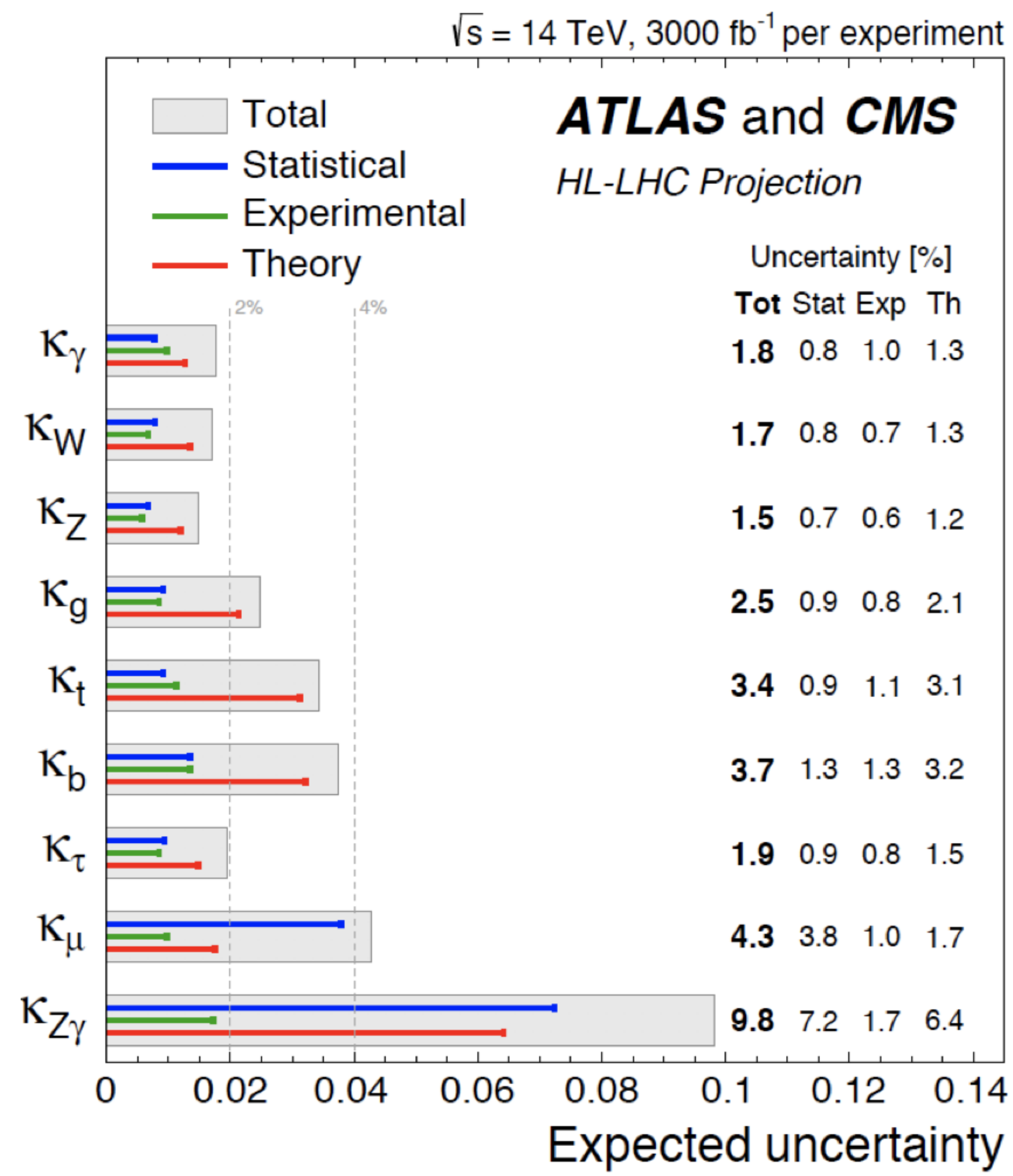
https://arxiv.org/pdf/1902.00134.pdf

Assume uncertainties can be reduced by factor of 2 wrt LHC

HL-LHC: Interpretation in κ framework

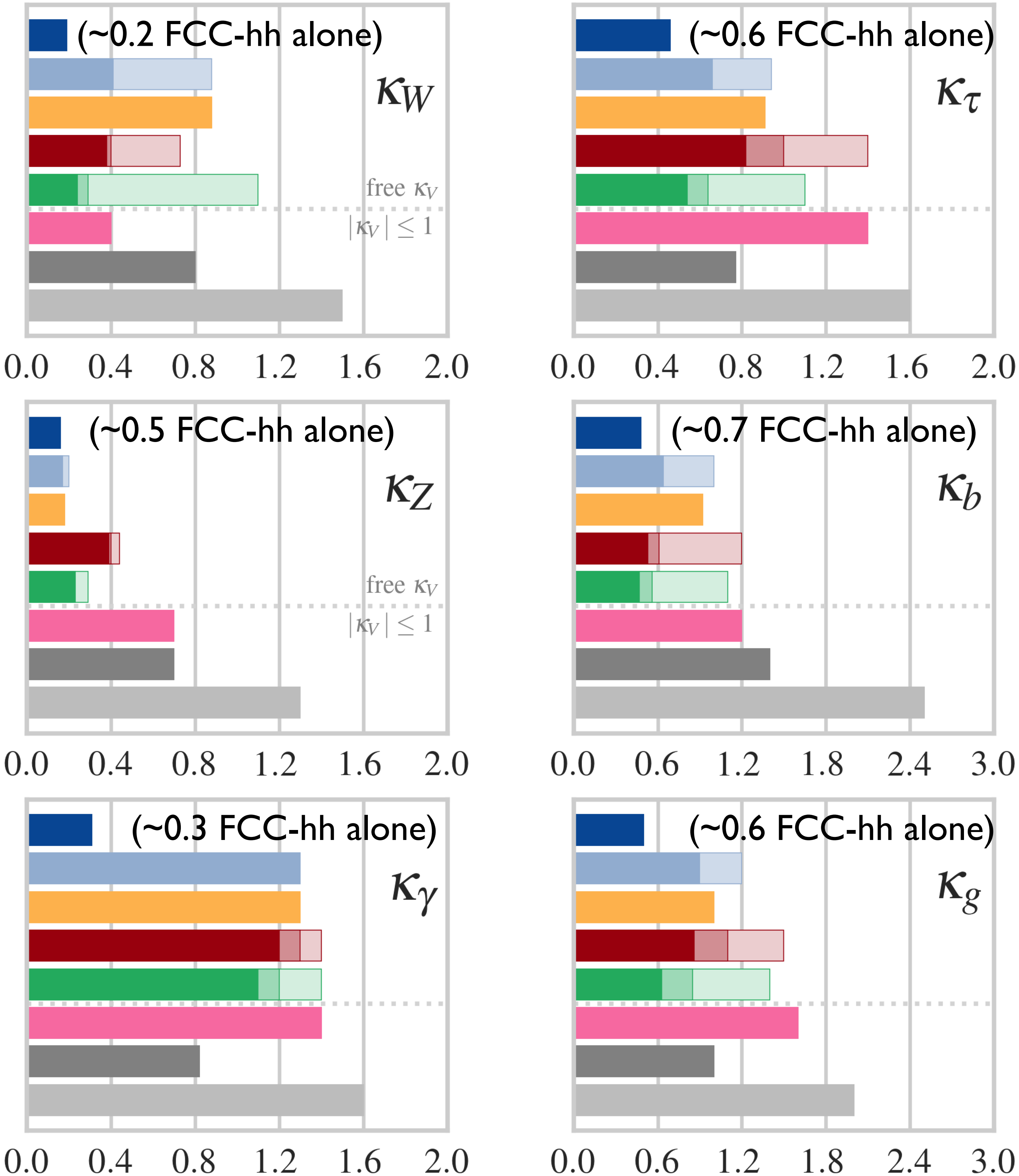


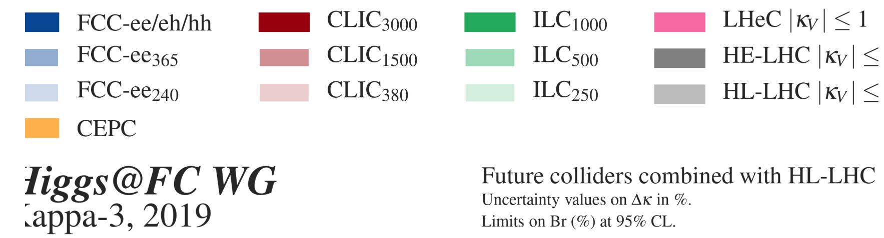
Many couplings reach ~2% precision
(Almost all) limited by **theory uncertainties**



Higgs at Future Colliders report: arXiv:1905.03764,

Higgs Precision at other future colliders





For HE-LHC assume another factor in 2 reduction in errors wrt HL-LHC

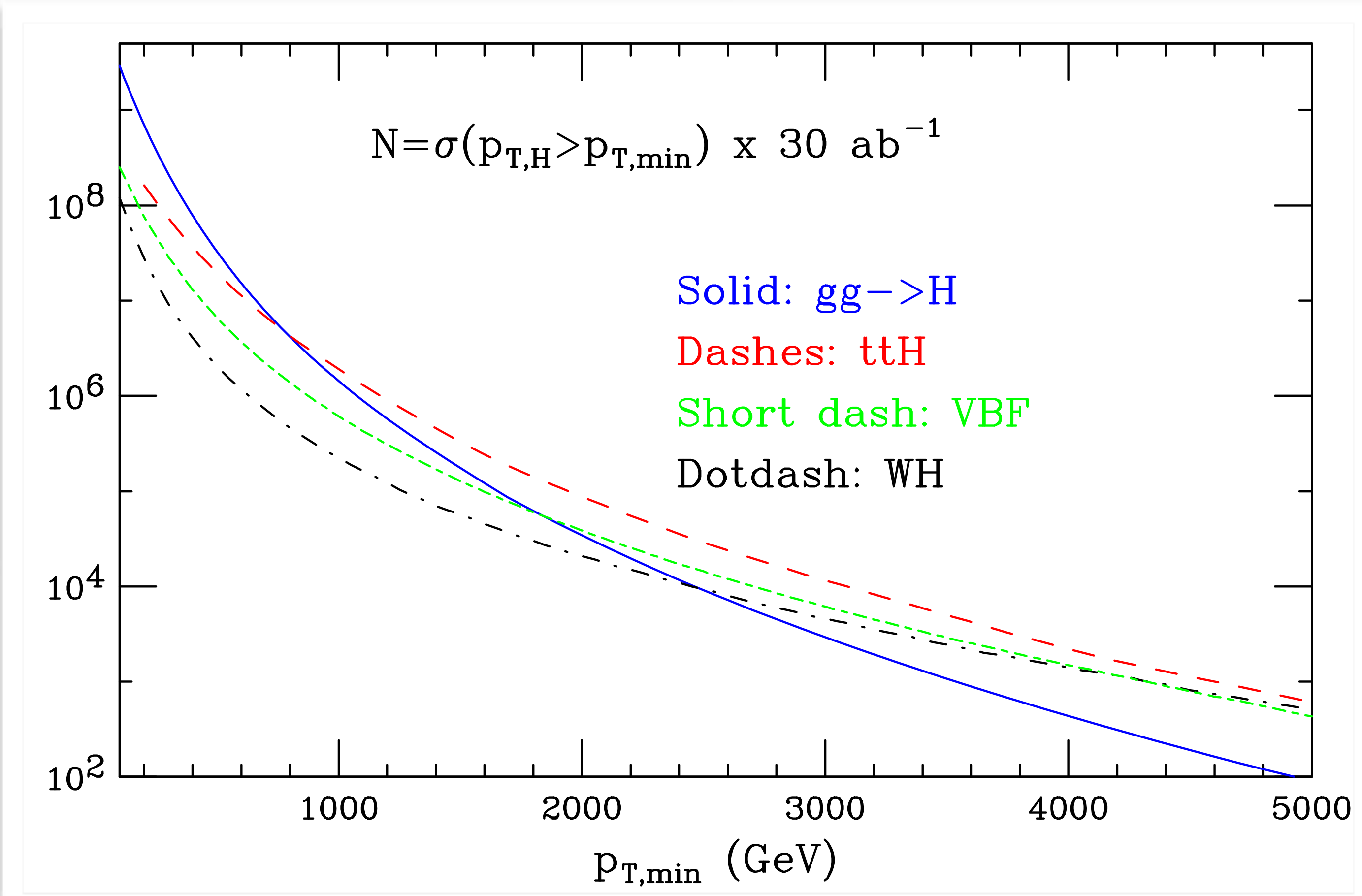
In many cases, FCC-hh obtains an order of magnitude improvement in precision over HL-LHC

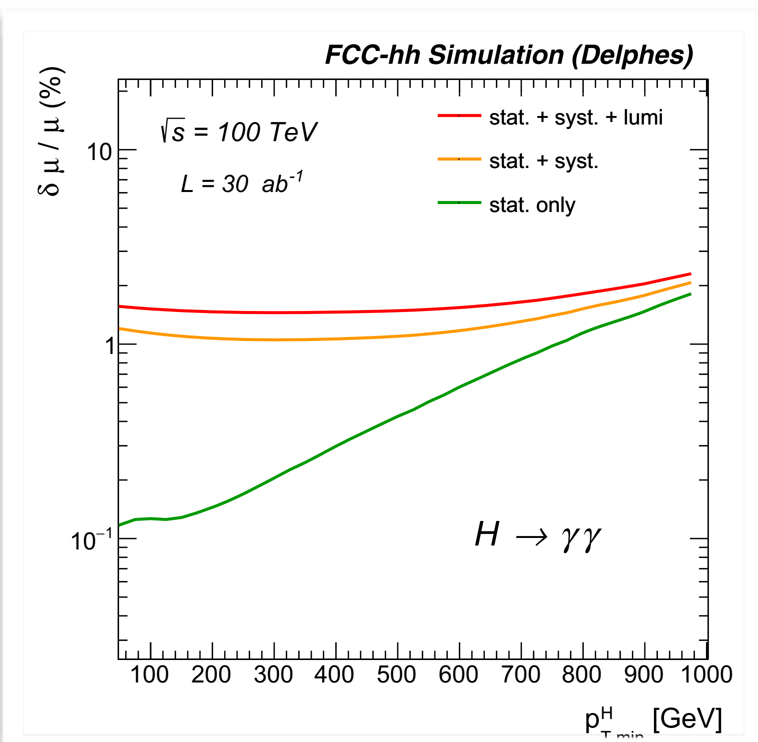
Only inclusive measurements are used

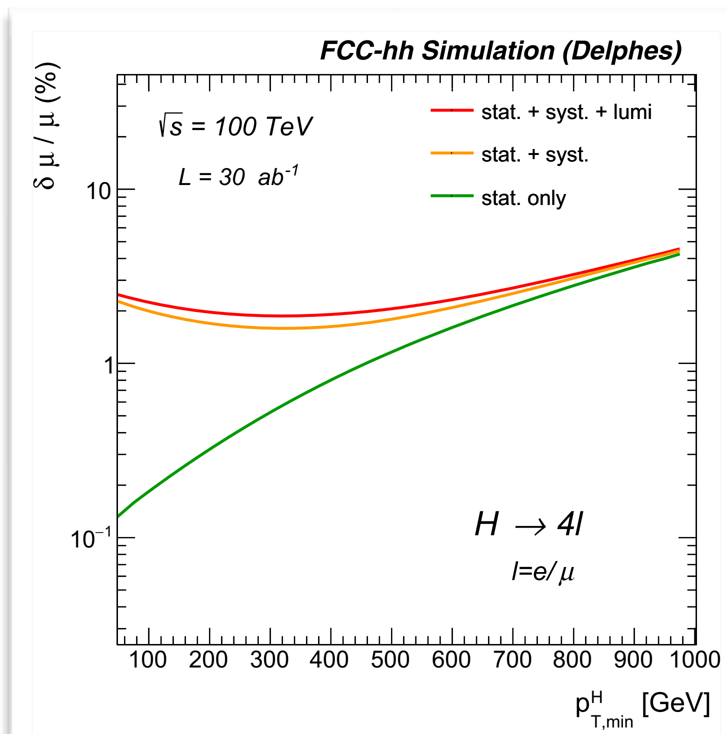
*FCC-ee crucial to obtaining model-independent Higgs coupling measurements: see talk by M. Klute

de Blas et al, Higgs Boson studies at future particle colliders

Higgs precision with differential distributions



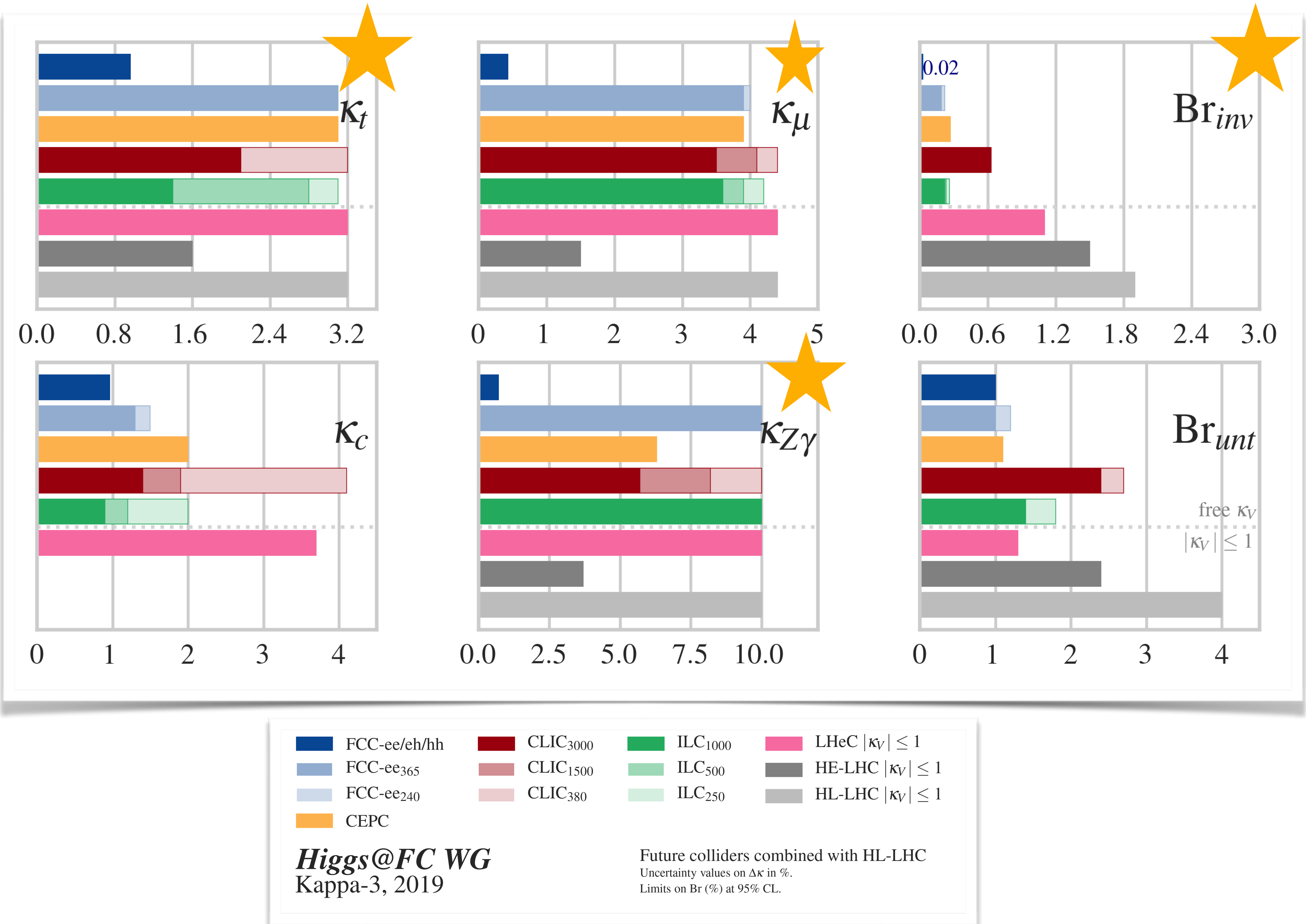




FCC Physics Opportunities

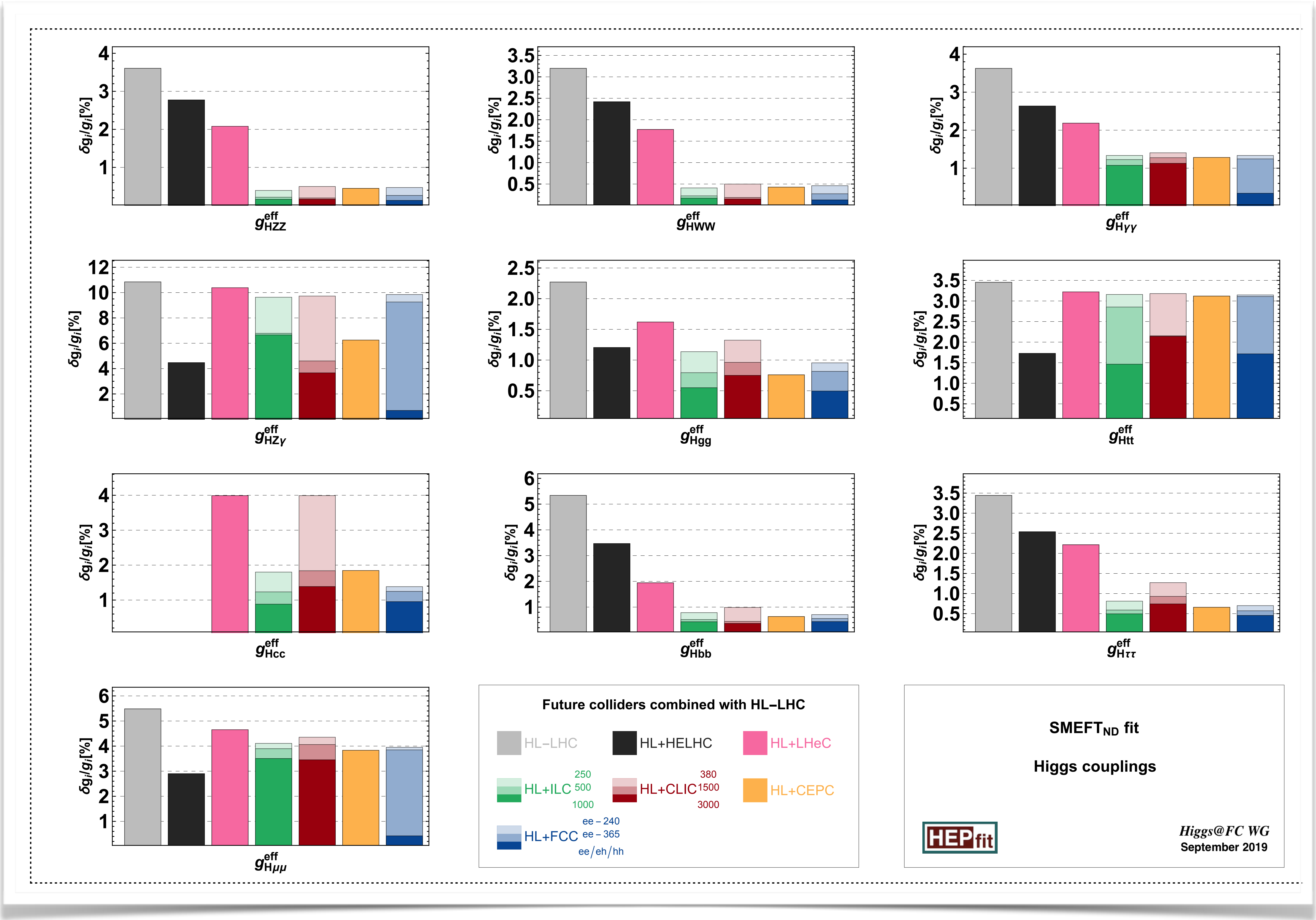
- There are changes to Higgs physics from moving to higher energies
  - Above 900 GeV, ttH production has the largest cross-section
- Many high p_T Higgs bosons
  - Can expect additional constraints on Higgs boson couplings from differential measurements

Higgs Precision at HE-LHC and FCC



de Blas et al, Higgs Boson studies at future particle colliders

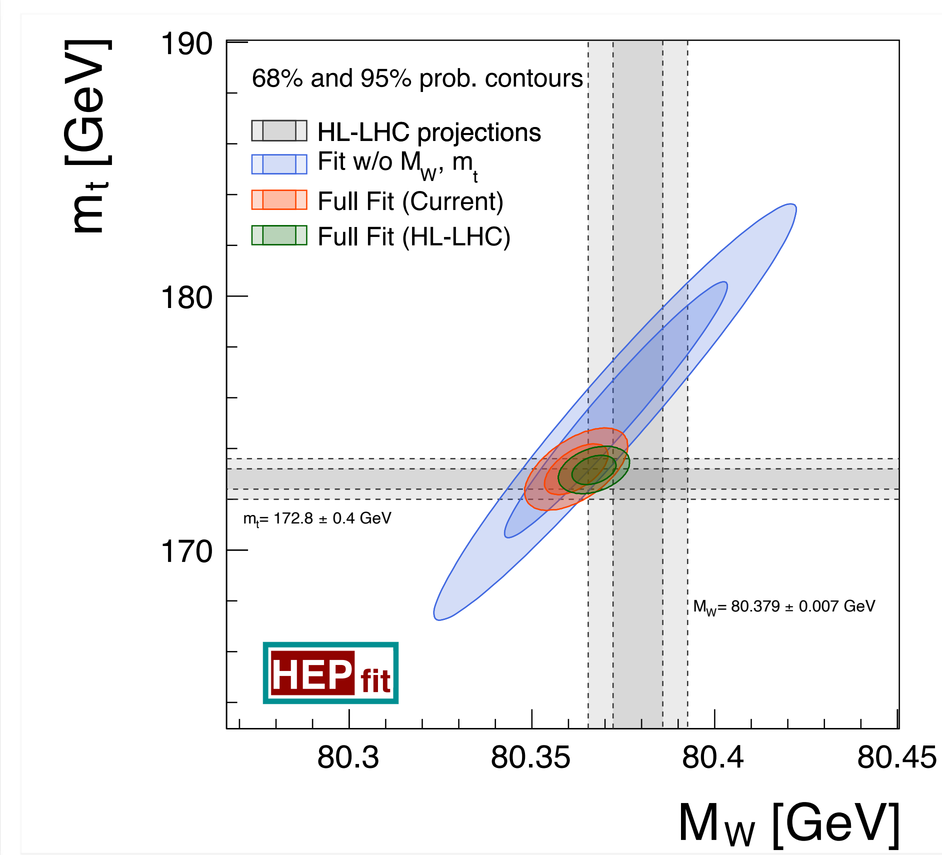
Interpretation within EFT Framework

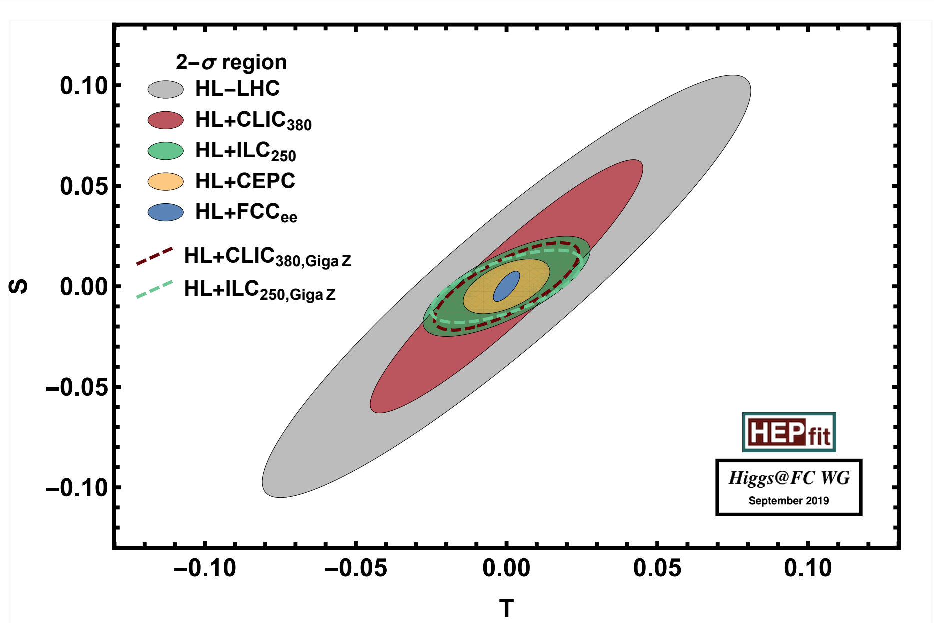


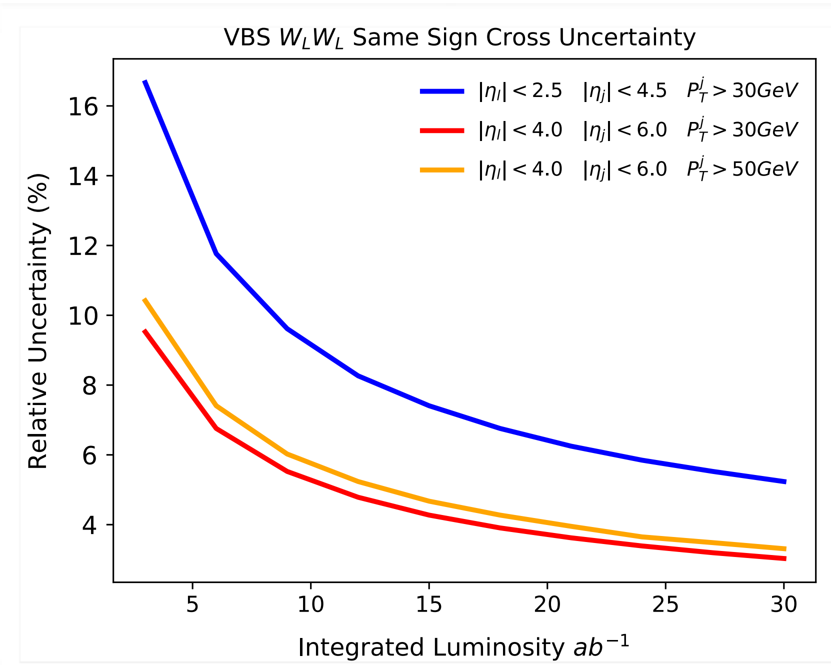
de Blas et al, Higgs Boson studies at future particle colliders

Other SM measurements

- HL-LHC: Higgs mass to ~20 MeV
- HL-LHC low pile up run (200 pb^{-1} at 14 TeV; 5-10 weeks of running)
  - W mass 6 MeV (requires precise PDF)
  - Top mass 0.2-1.2 GeV (relation to pole mass)
- Projections for FCC-hh reach 3% on VBS $W_L W_L$



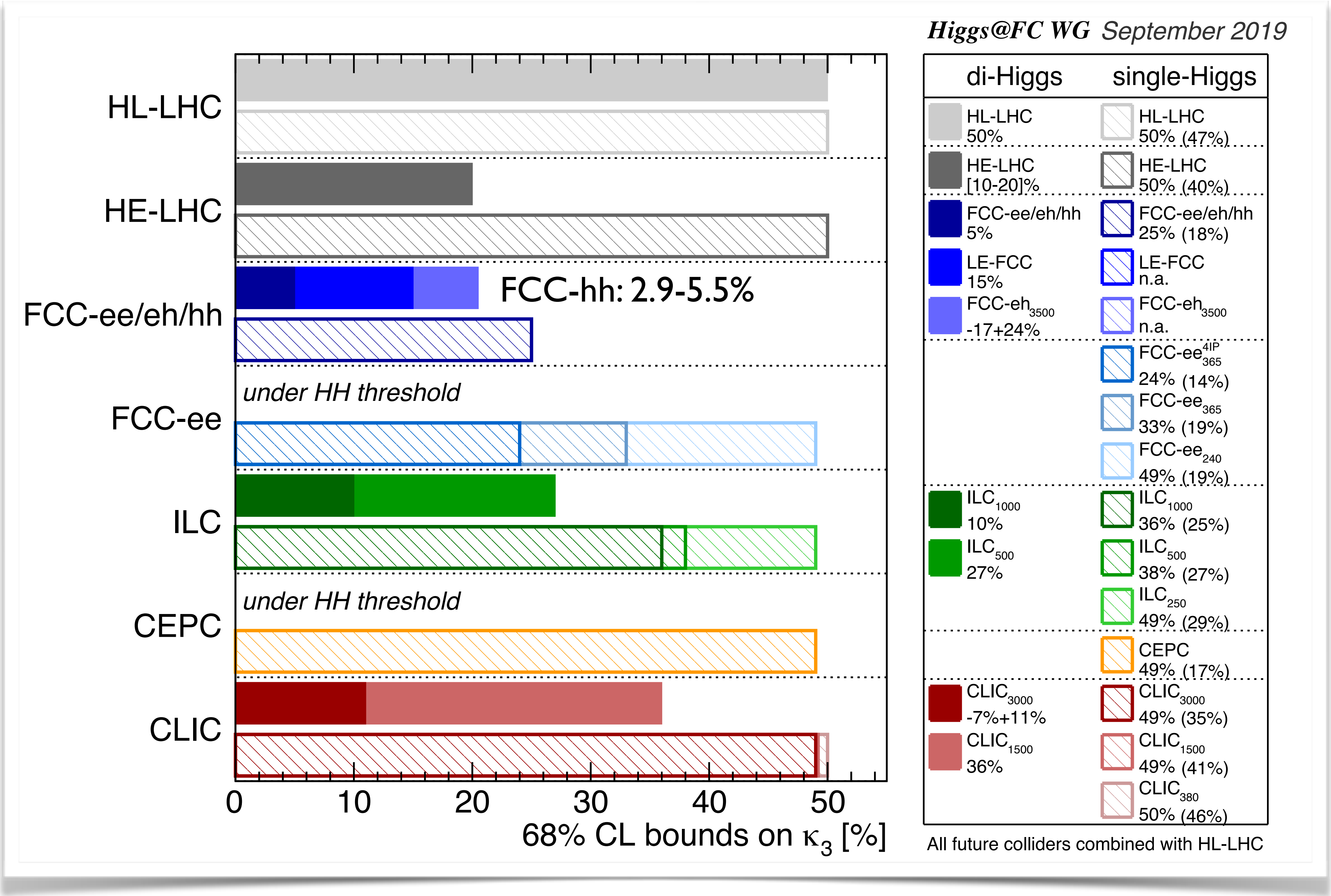




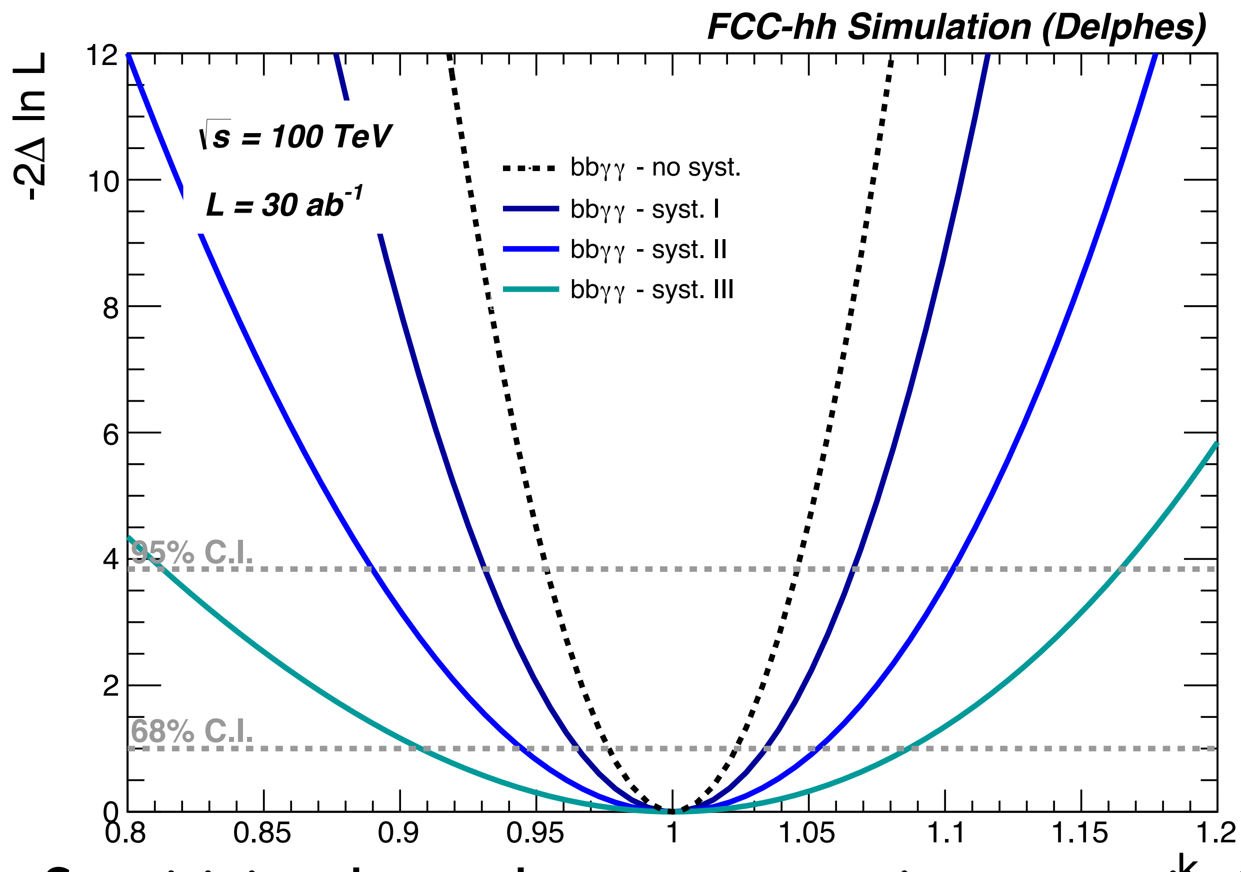
Clearly expect lepton colliders to have superior performance in most cases where they have energy reach, but what accuracy could we get from FCC-hh?

Higgs Self-coupling

- Key physics deliverable to probe mechanism of EW symmetry breaking
  - Direct searches
  - Indirect constraints from single Higgs production through loop effects



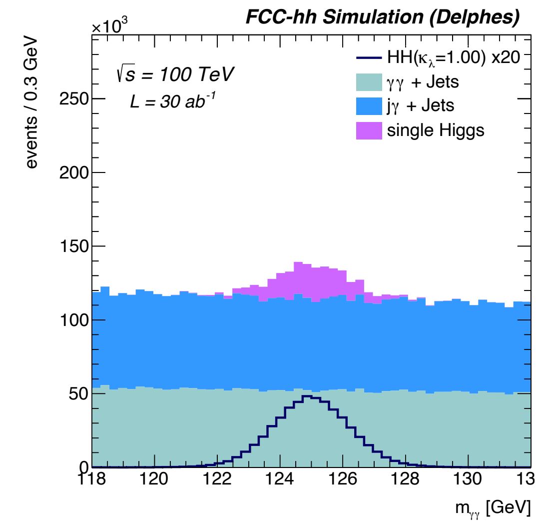
Example: bb$\gamma\gamma$ channel

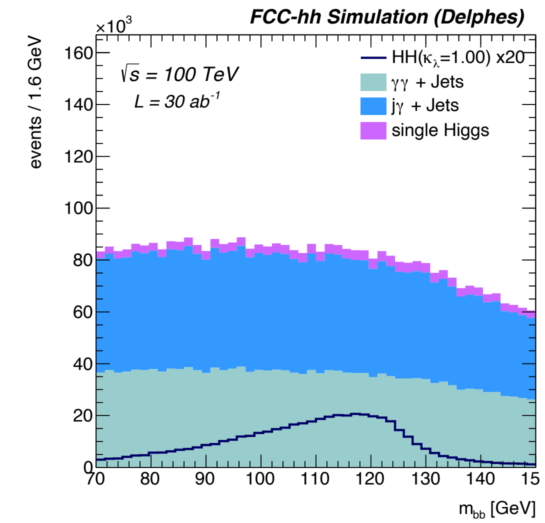


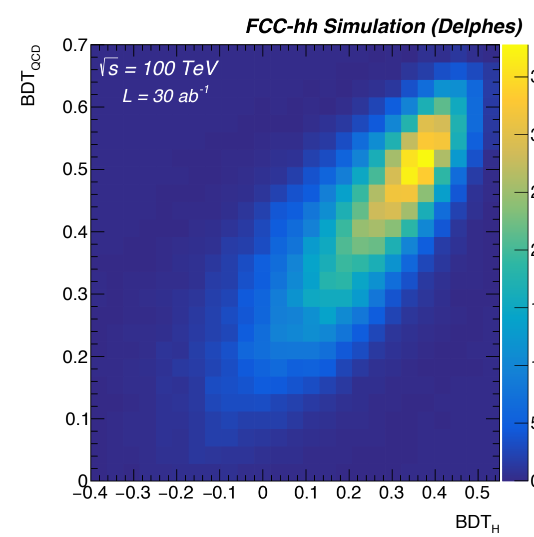
Sensitivity depends on systematic uncertainties

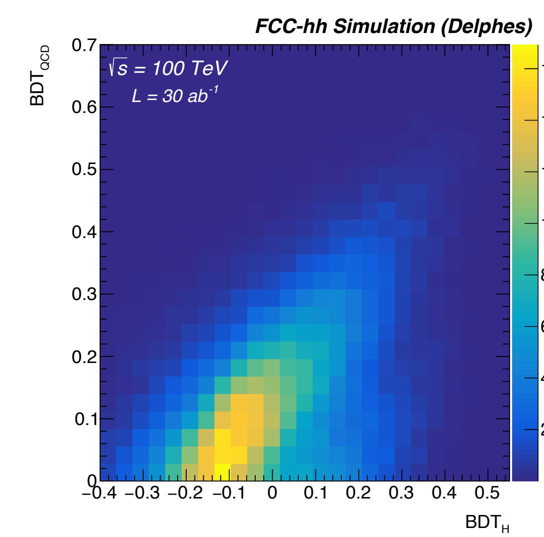
Uncertainty source	syst. I	syst. II	syst. III	Processes
b-jet ID eff. /b-jet	0.5%	1%	2%	single H, HH, $t\bar{t}$
τ-jet ID eff. /τ	1%	2.5%	5%	single H, HH, $t\bar{t}$
γ ID eff. /γ	0.5%	1%	2%	single H, HH
$\ell = e$-μ ID efficiency	0.5%	1%	2%	single H, HH, single V, VV, $t\bar{t}V$, $t\bar{t}VV$
single H cross section	0.5%	1%	1.5%	H
$t\bar{t}$ cross section	0.5%	1%	1.5%	H
luminosity	0.5%	1%	2%	single H, HH, single V, VV, $t\bar{t}$, $t\bar{t}V$, $t\bar{t}VV$
HH cross section	0.5%	1%	1.5%	HH

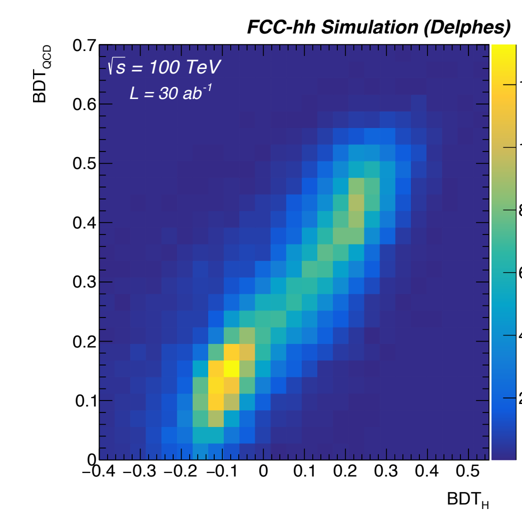
DELPHES simulation; no explicit pile-up











BDT based on kinematic information

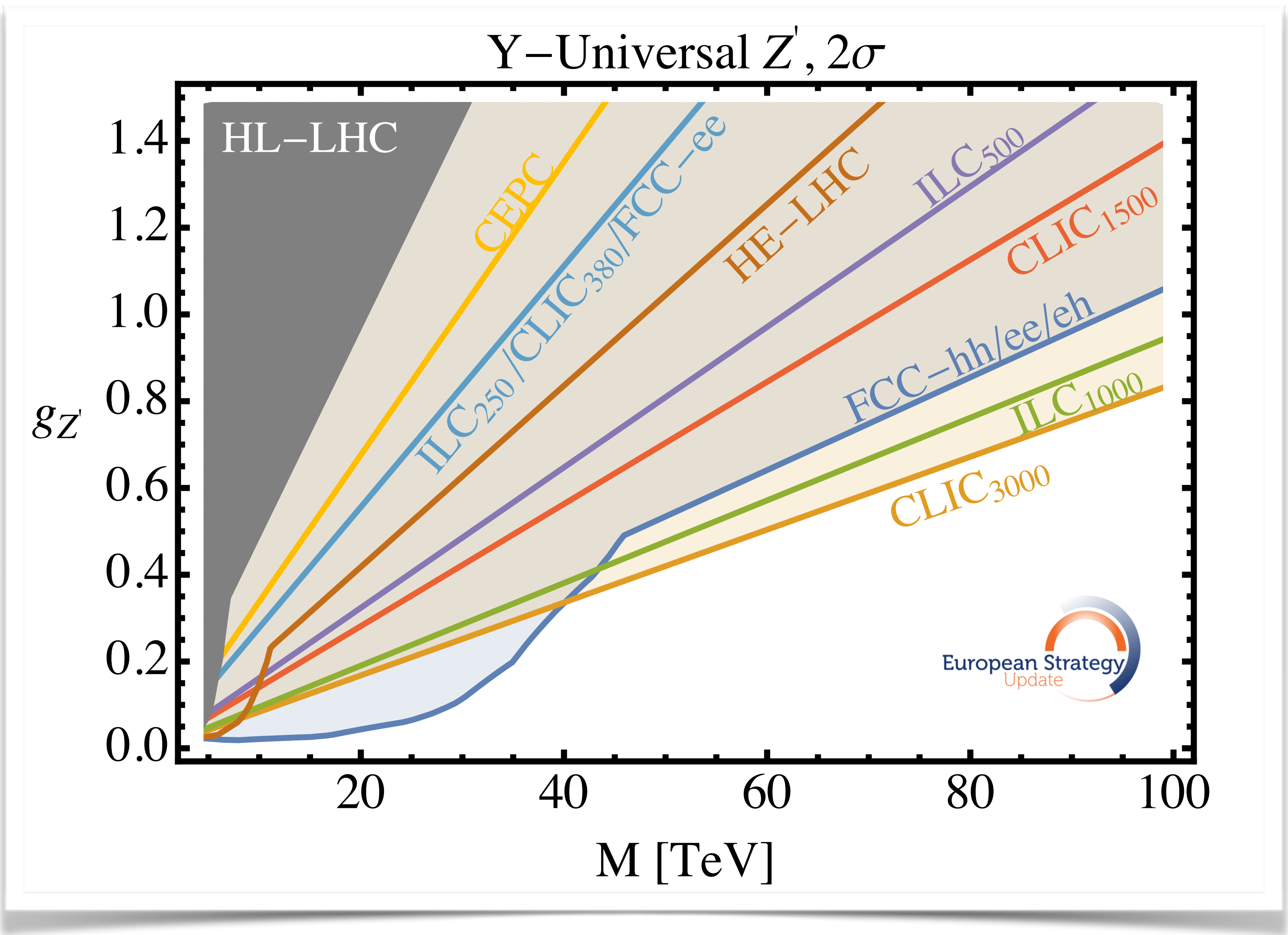
Mangano, Ortona, and Selvaggi, arXiv:2004.03505

Searches for New Physics

Hadron collider are very powerful at directly probing for new physics. A challenge in making the physics case is deciding which directions are the most important to probe

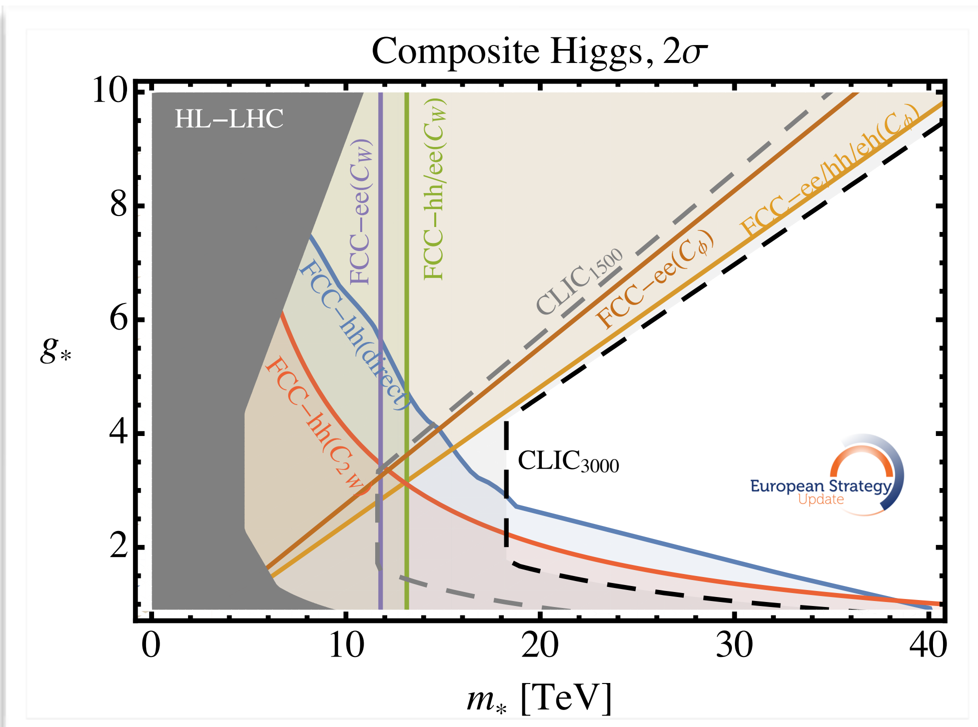
New Interactions or Particles

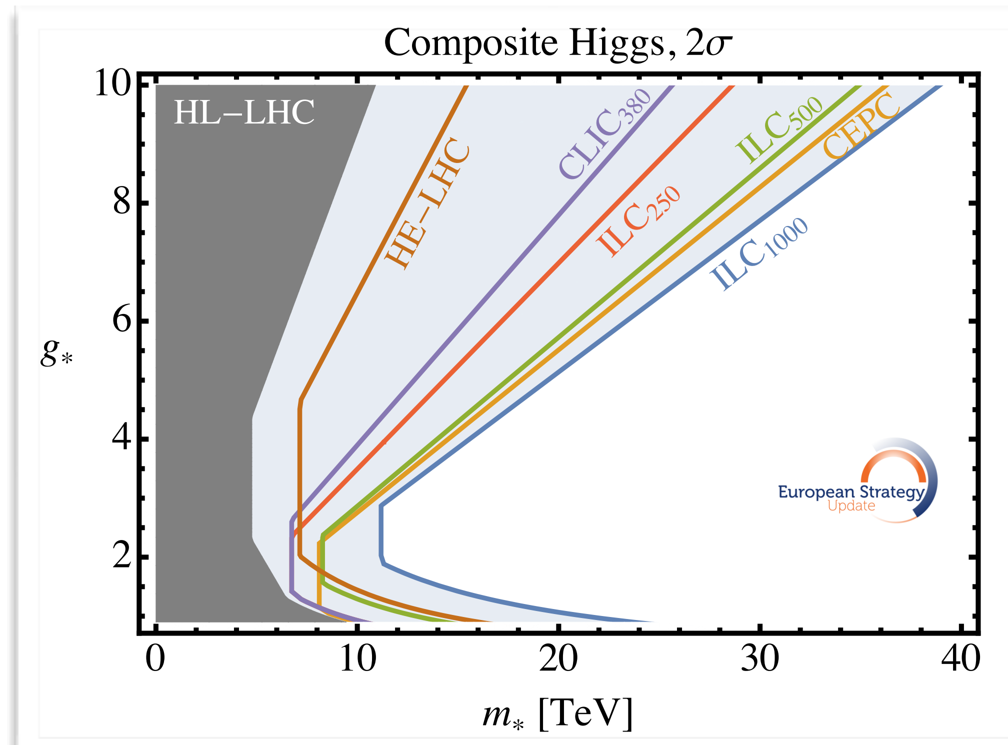
- Are there any new particles or interactions beyond the SM?
- Direct (peak) or indirect (couplings)
- Direct observation
  - M $\lesssim$ 0.3-0.5$\sqrt{s}$ for hadron colliders
- Benchmark: simple sequential Z’ model

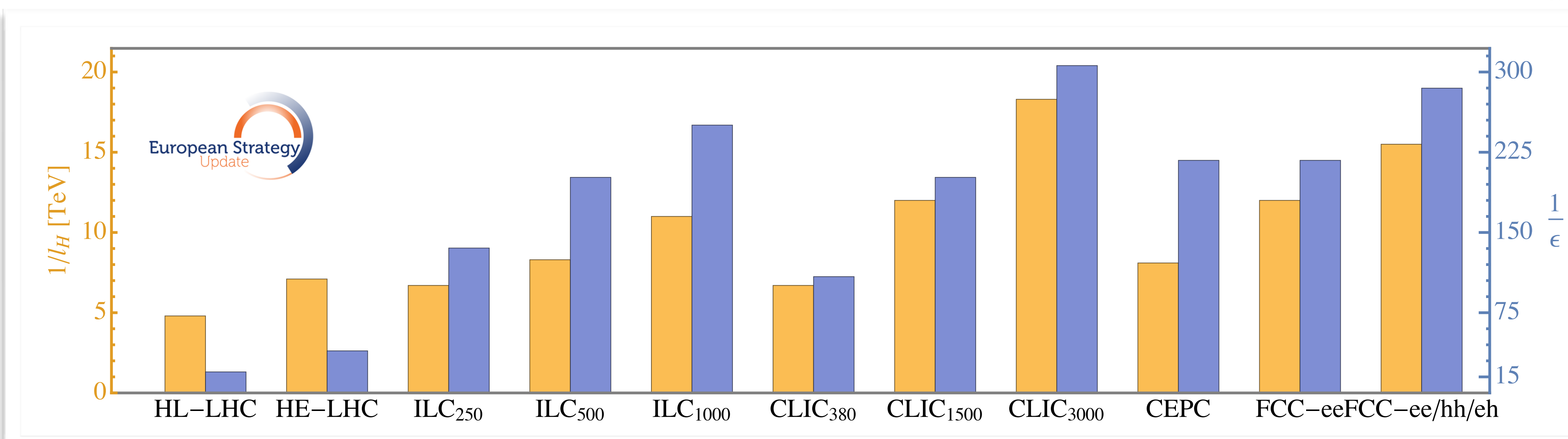


Higgs Compositeness

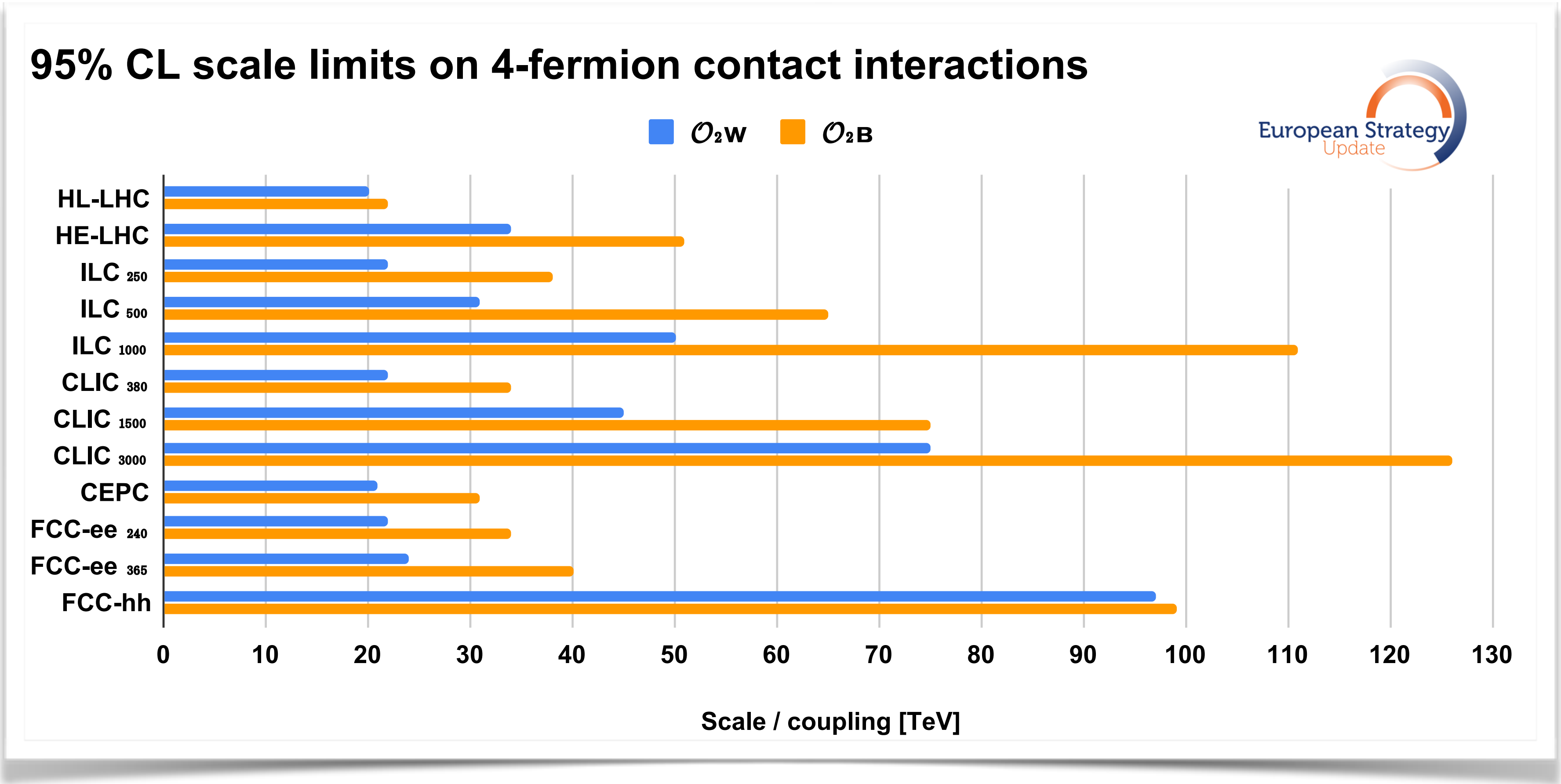
- Is the Higgs boson an elementary particle or composite?
- Limits from Higgs couplings, Drell-Yan searches
- Obtain limits on compositeness scale from ~1-4 TeV



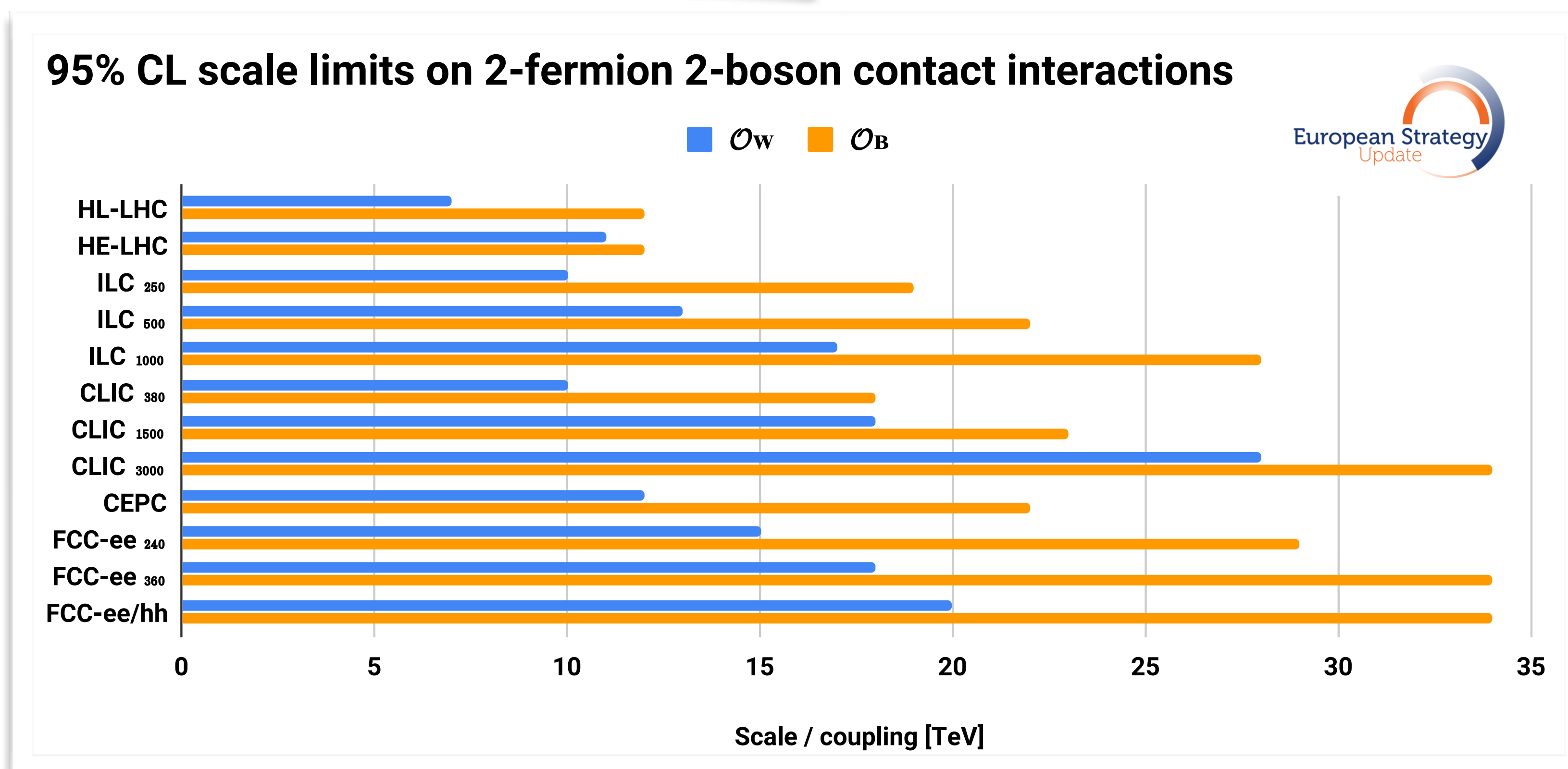




Contact Interactions



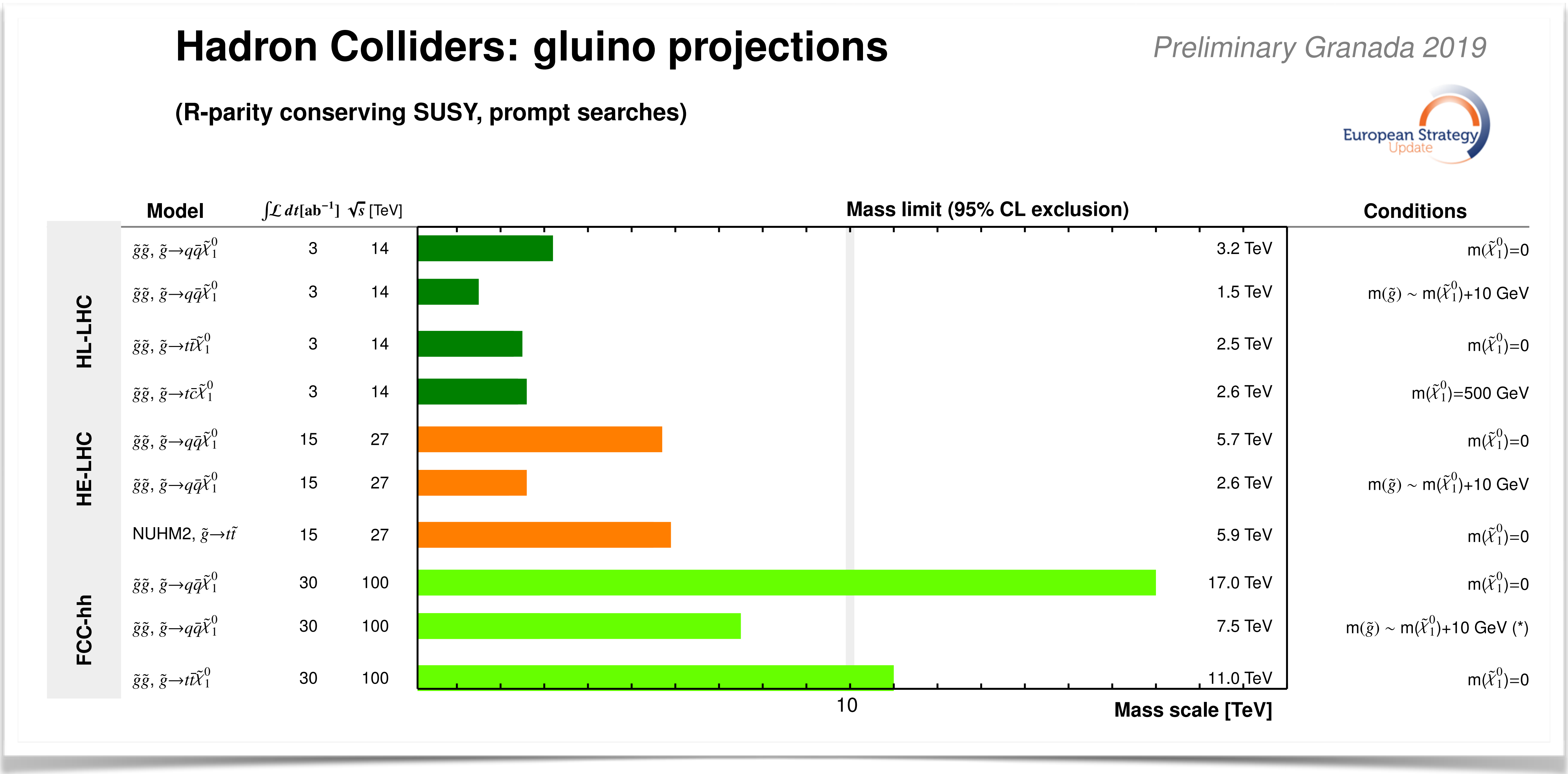
Hadron collider sensitivity via Drell-Yan production



New physics in the interaction between the Higgs and vector bosons

Hadron collider sensitivity via Z boson p_T distribution

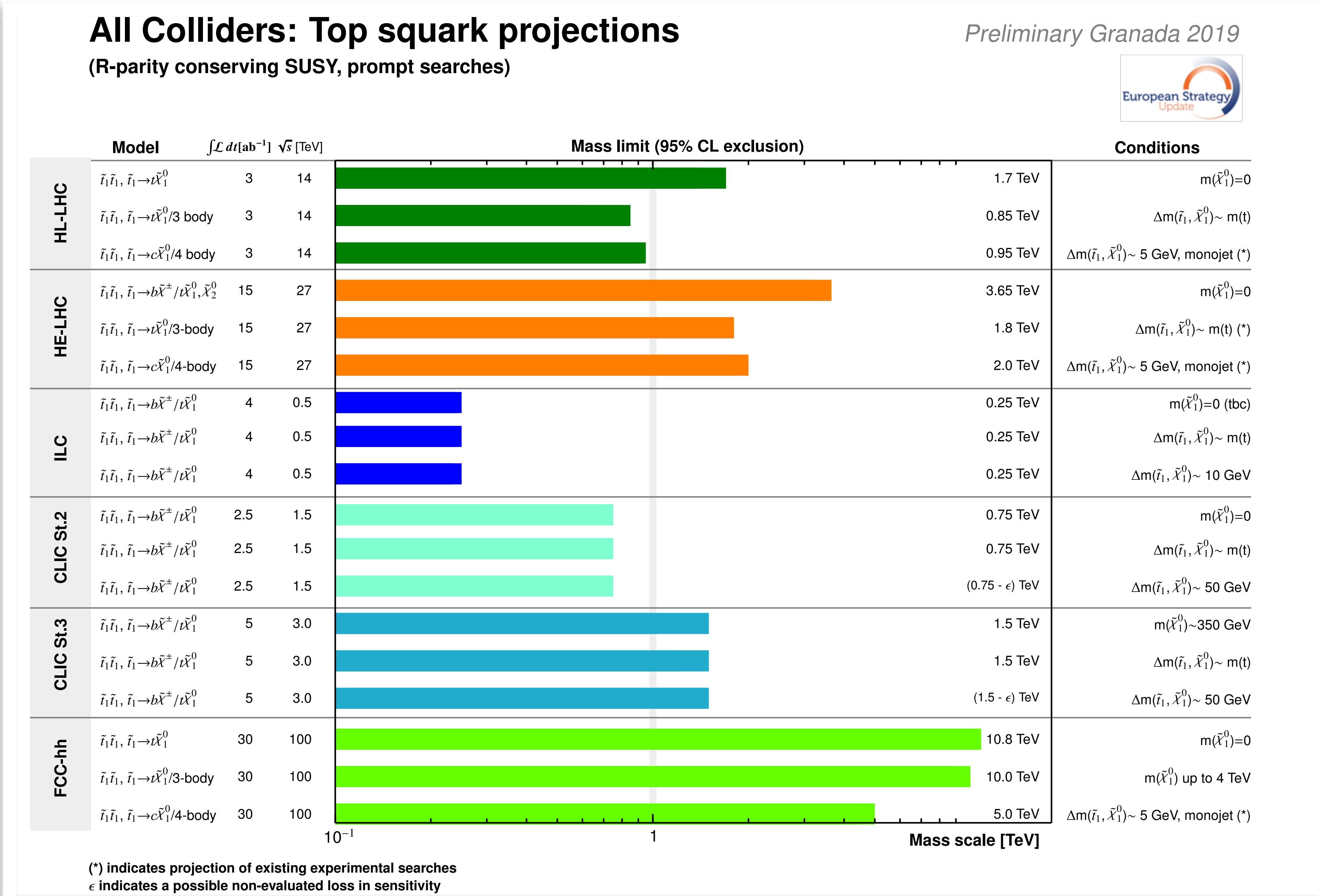
Strong SUSY: gluinos



HE-LHC extends HL-LHC mass reach by a factor of ~2

FCC-hh extends HL-LHC mass reach by a factor of ~5

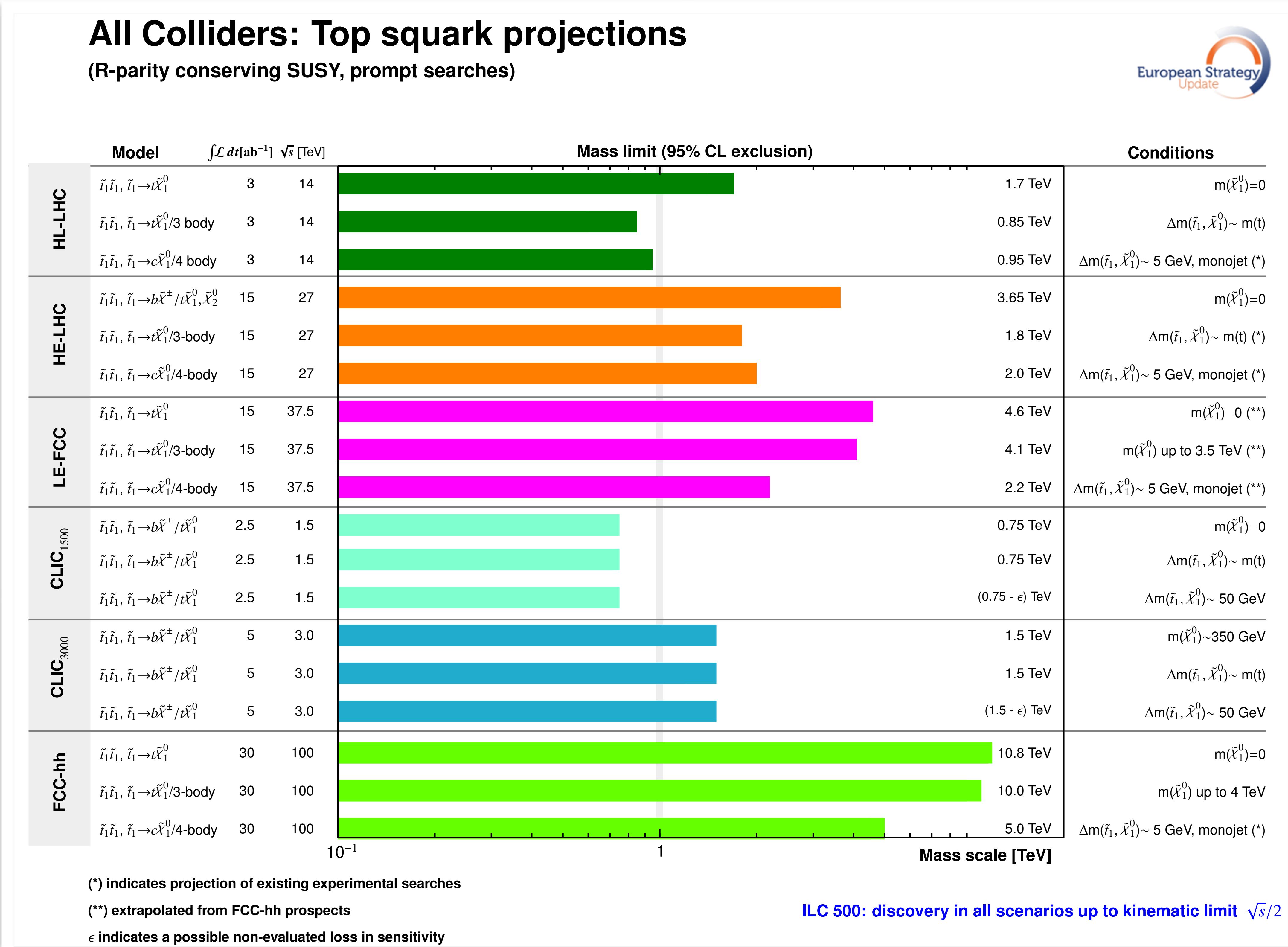
Strong SUSY: squarks



HE-LHC extends HL-LHC mass reach by a factor of ~2

FCC-hh extends HL-LHC mass reach by a factor of ~5-12

Strong SUSY: Squarks

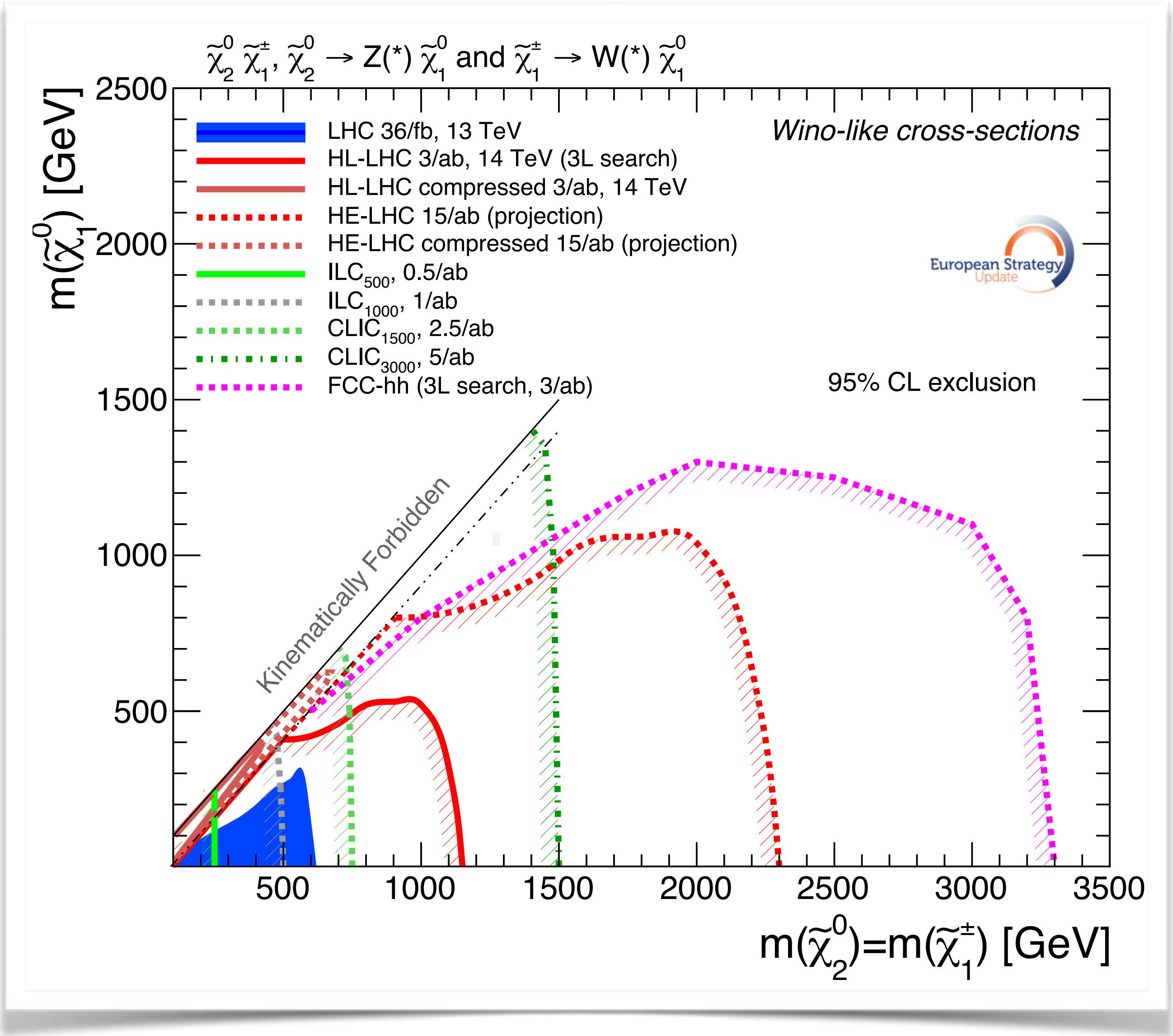


HE-LHC extends HL-LHC mass reach by a factor of ~2

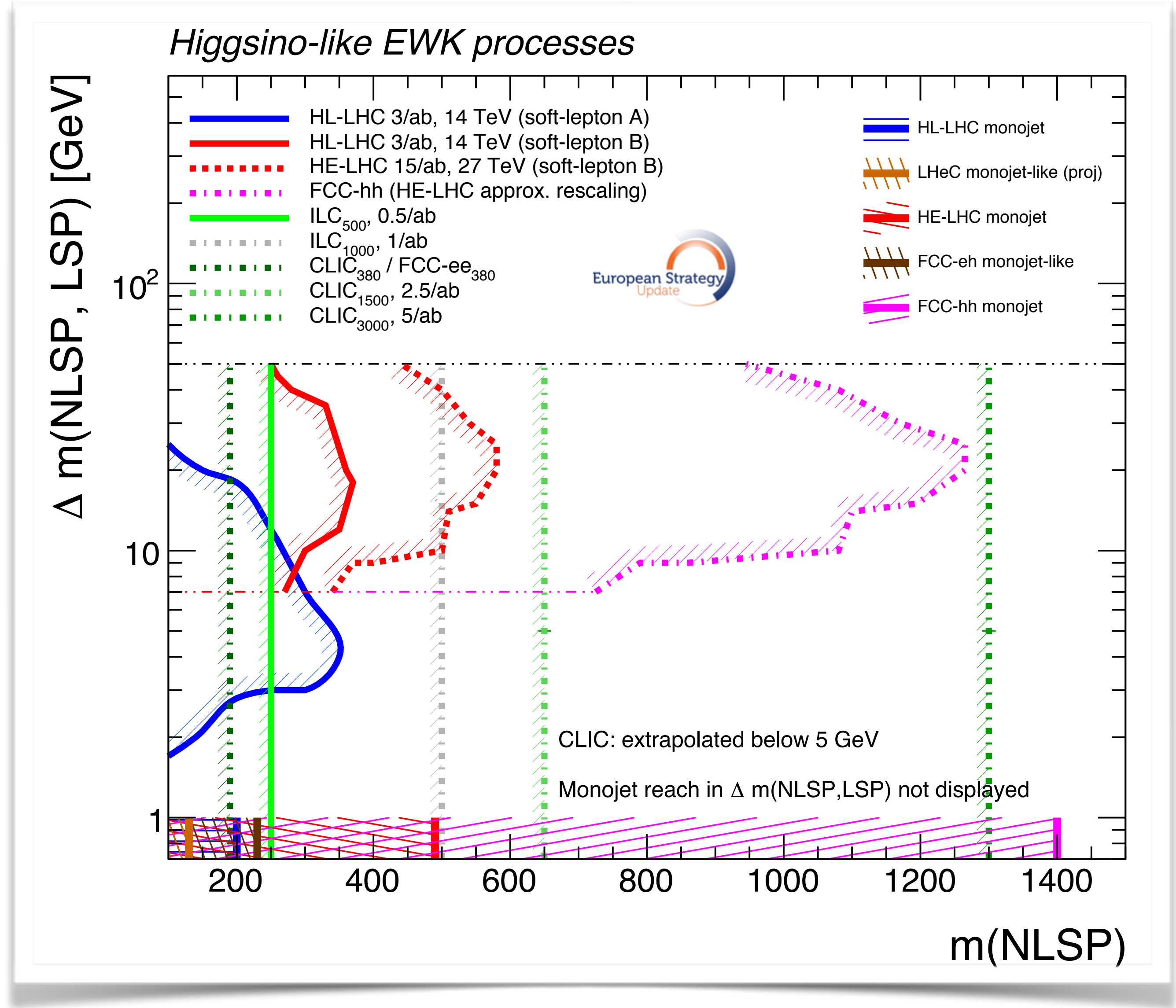
FCC-hh extends HL-LHC mass reach by a factor of ~6

Electroweak SUSY

Wino

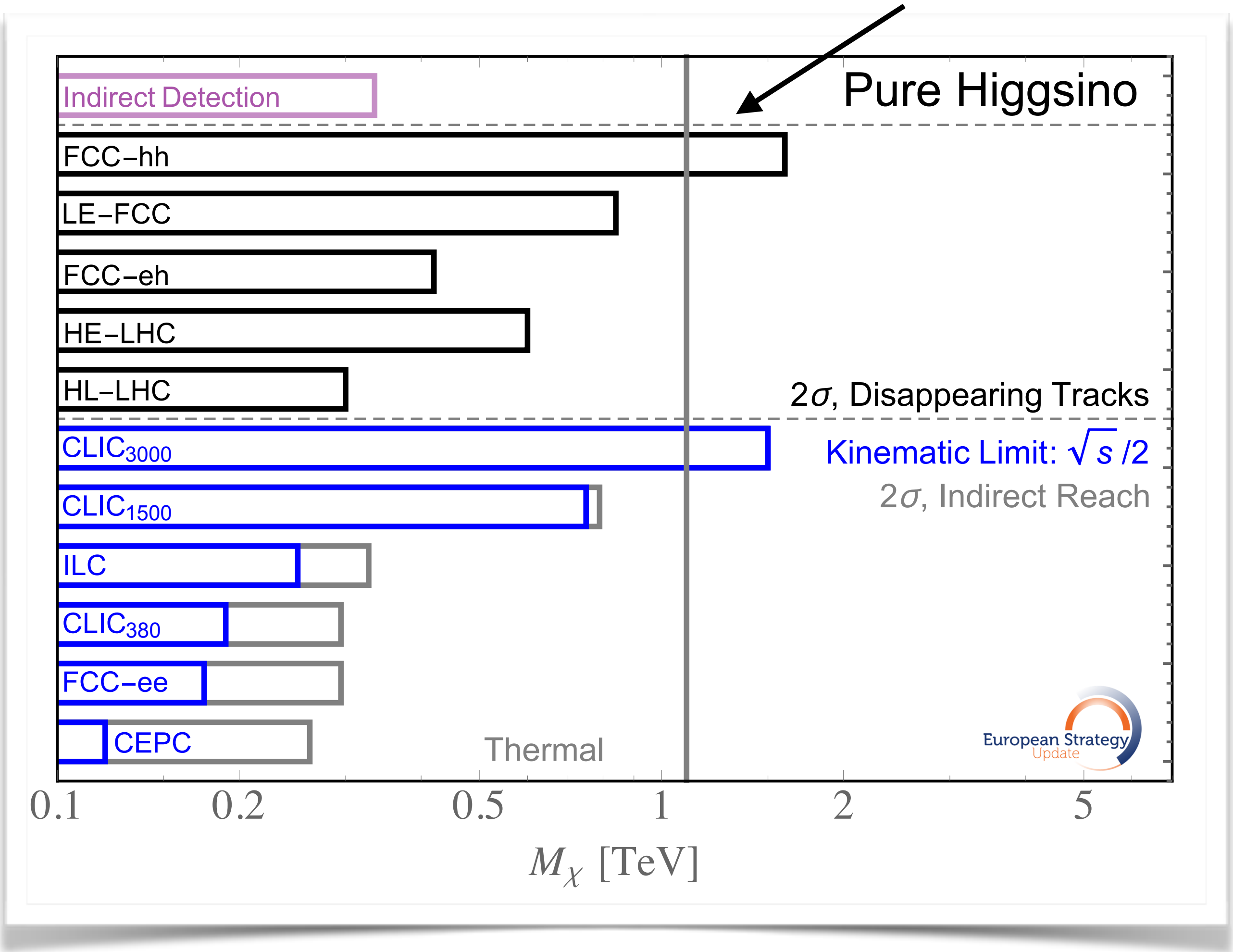


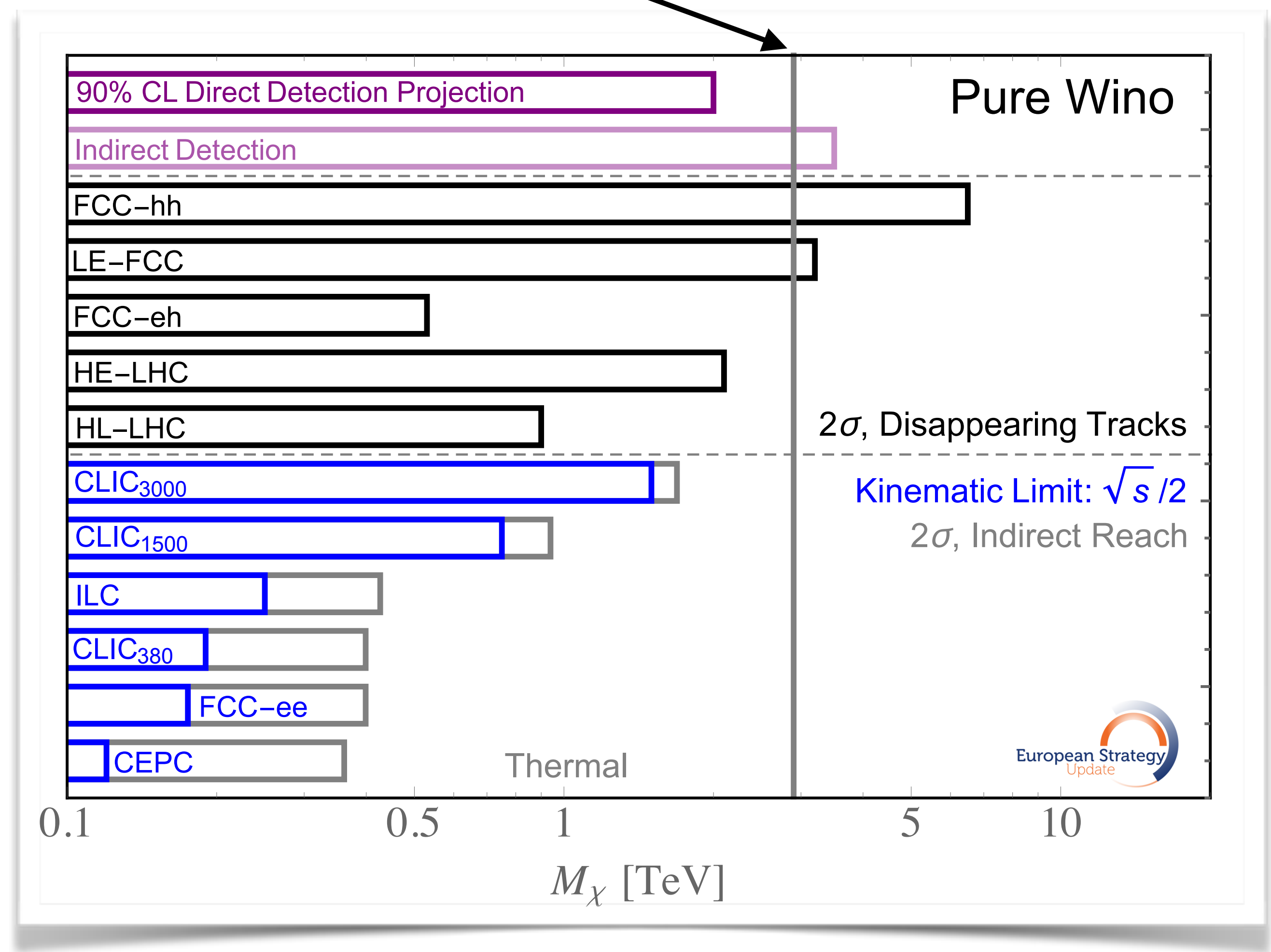
Higgsino



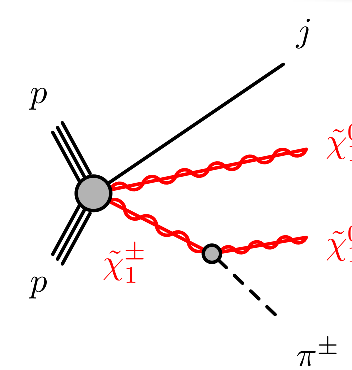
Higgsino and Wino Searches

Upper limit from DM abundance

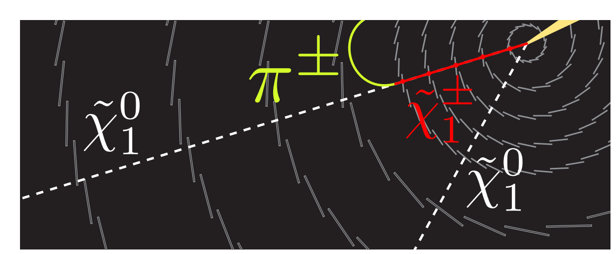




- Searches for the case where the Higgsino or the Wino are dark matter candidates as the LSP in SUSY

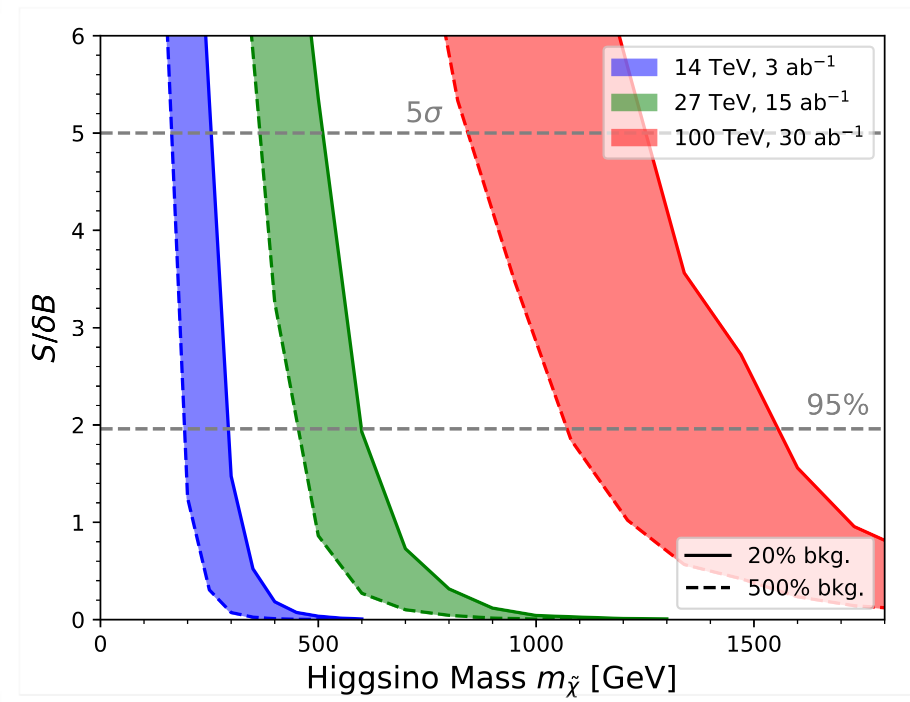


- At hadron colliders, the most effective search technique is called "disappearing tracks"

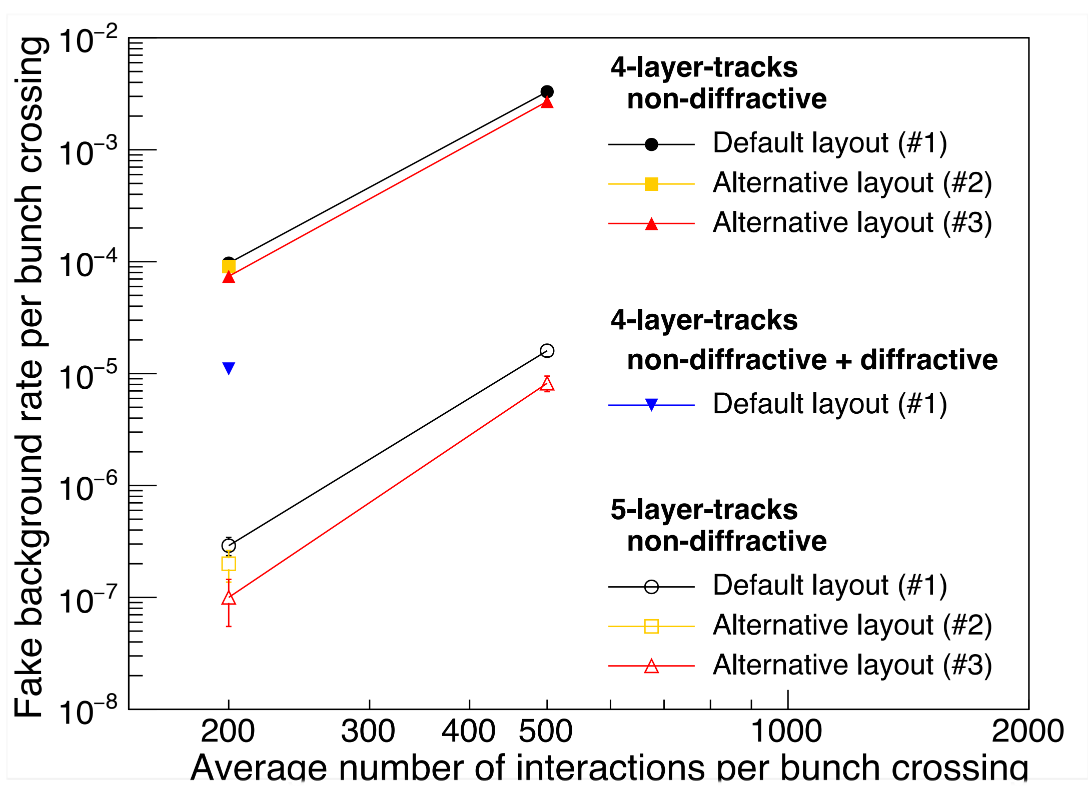


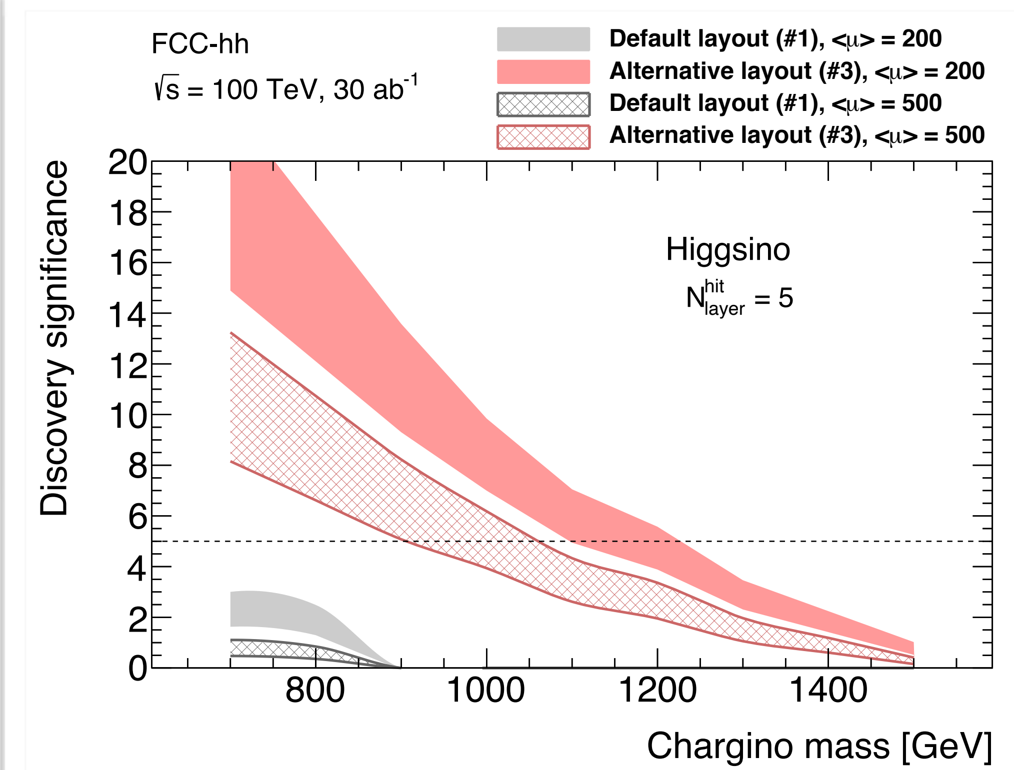
Example: Disappearing Track for Higgsinos

- The FCC-hh could probe Higgsinos up to ~1 TeV (full range a WIMP candidate)
- Reach depends strongly on detector design and amount of pile-up
- How can we best design our tracking detectors for such searches?



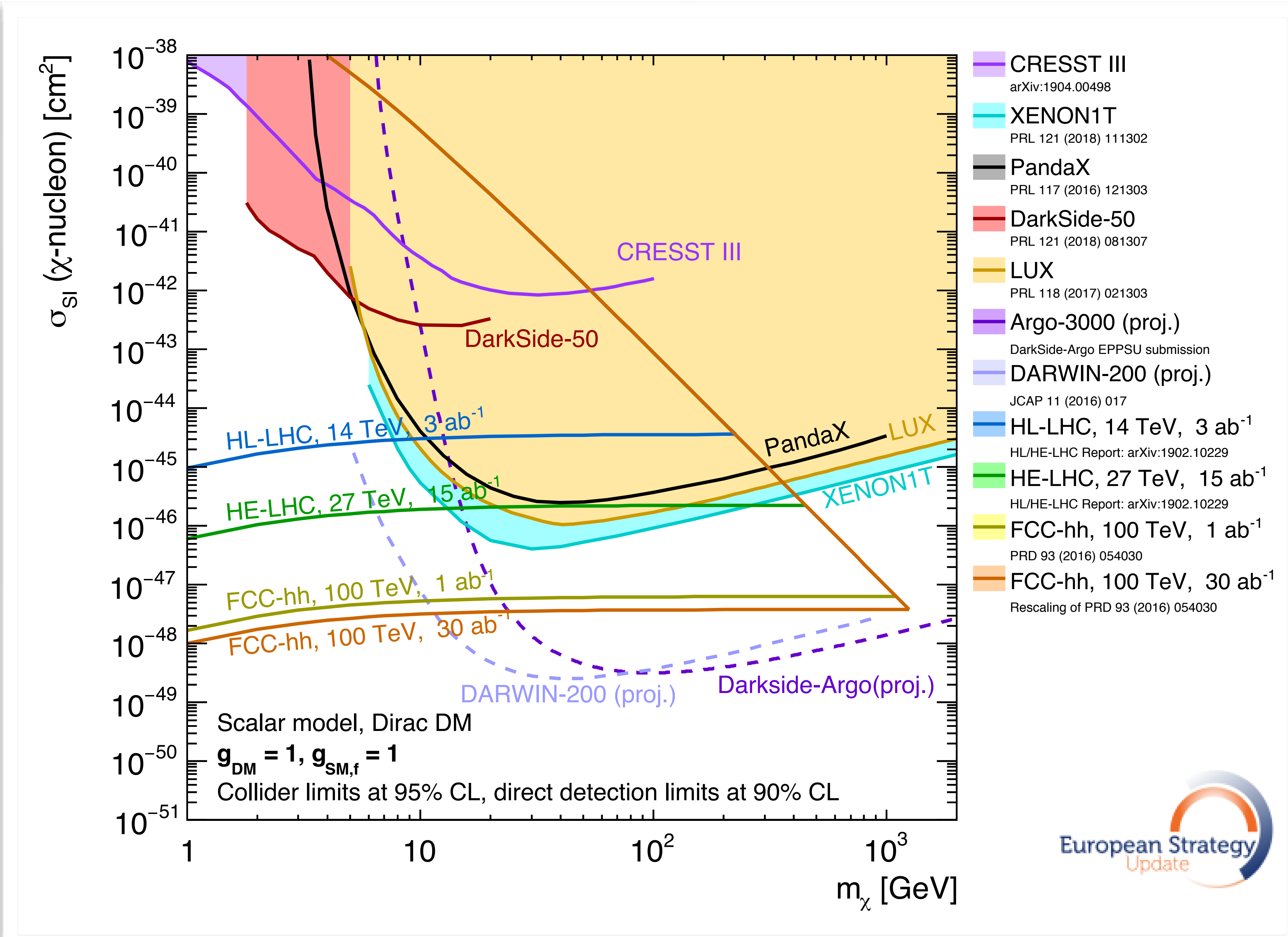
Tan, et al. EW DM at Future Hadron Colliders





Terashi, et al. Disappearing tracks at FCC-hh

Dark Matter

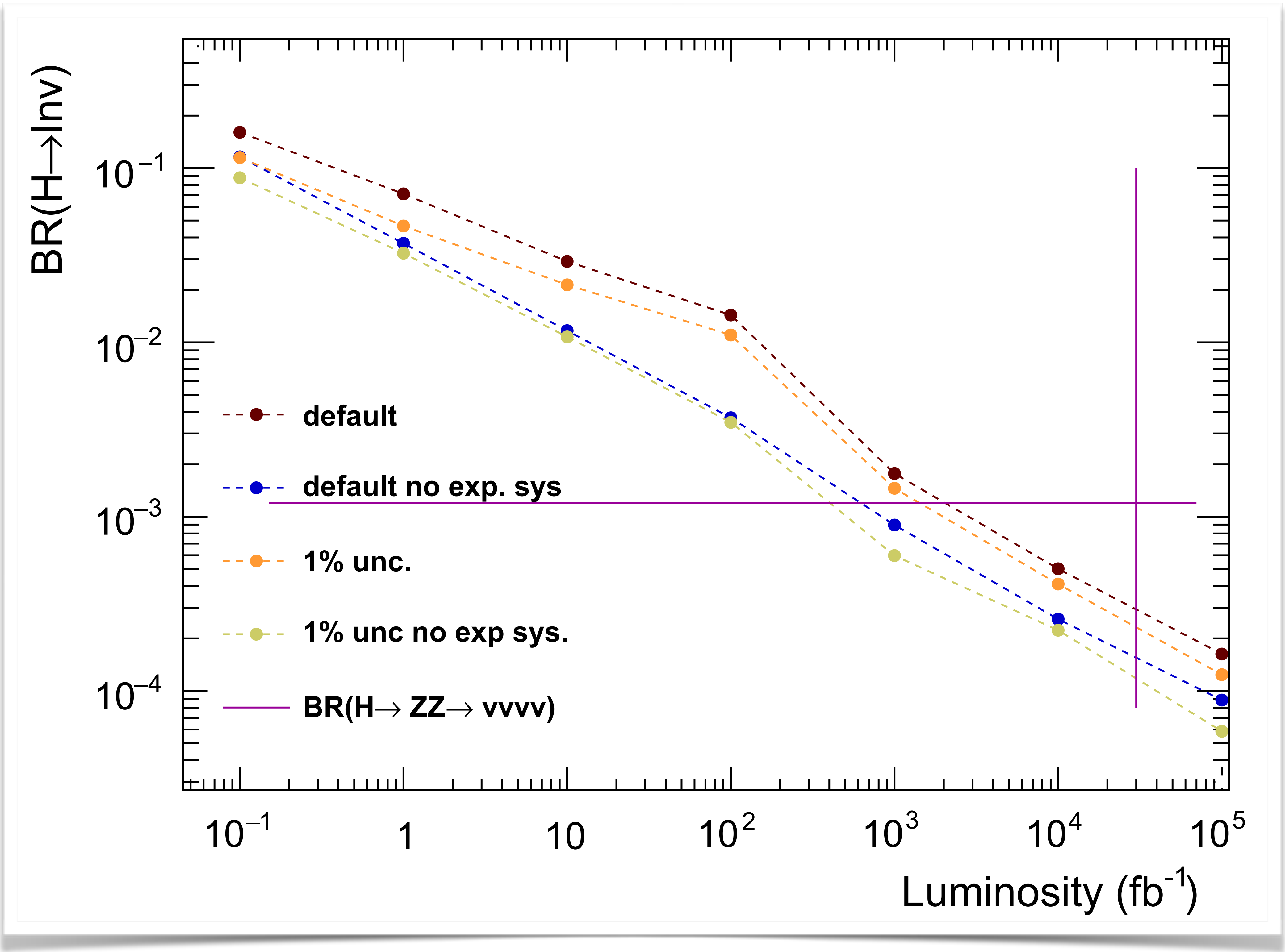


Model-dependent limits from colliders probe the low mass range

Based on results for Higgs→invisible decays

Example: Higgs→invisible results

Fit MET distribution in VBF Higgs production



FCC Physics Opportunities

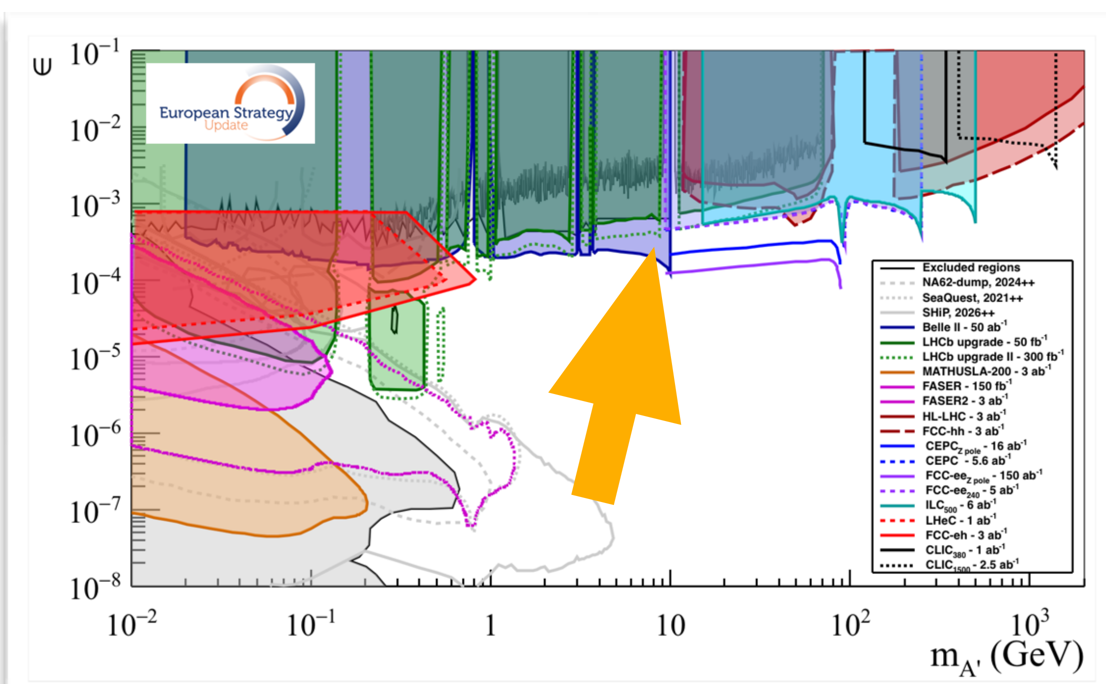
Feebly Interacting Particles (FIPs)

- Range of possibilities and models

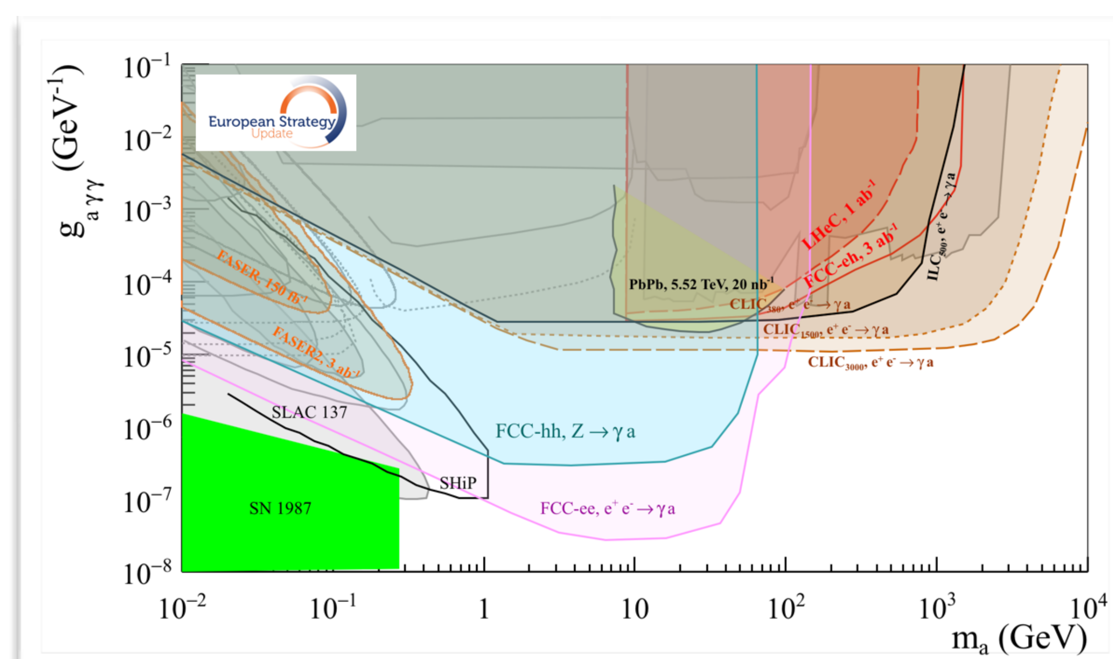
Portal	Coupling
Vector (Dark Photon, A_μ)	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Fermion (Sterile Neutrino, N)	$y_N L H N$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$

- Hadron colliders play a complementary role to targeted experiments

Dark Photon



Axion Like Particles (ALPs)



How could we include $pp \to a \to \gamma\gamma$?

Bauer et al, Axion-Like Particle at Future Colliders

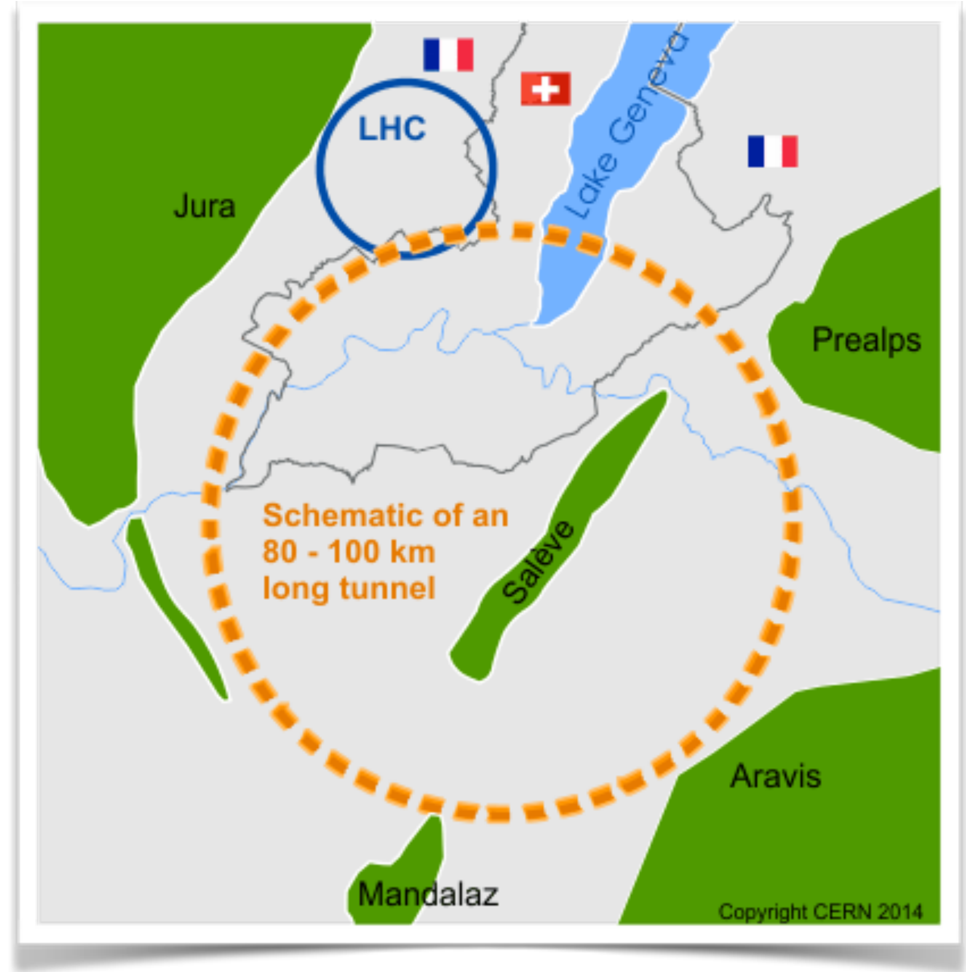
Conclusion

- Critical turning point for our field as we evaluate options and try to converge on what machine(s) we want to build next
- Short review of future hadron colliders
  - HL-LHC, HE-LHC, FCC-hh and SppC
- Key physics capabilities include precision Higgs couplings, the Higgs self-coupling and an extensive range of BSM searches
- Some ideas and open questions
  - Pile up — what impact does 1000 collisions have? How can we mitigate it?
  - What energy? i.e. why 100 TeV vs 80 or 120 TeV?
  - Higgs coupling precision from differential measurements
  - How could new detector technologies impact physics reach?
    - Can we design trackers to improve long-lived particle searches?
    - How does 4D tracking improve physics capabilities?
  - Systematics: particularly theory systematics
    - Important to address in general; also relevant for comparing physics reach between hadron and lepton colliders

Backup

FCC-hh

- New tunnel ~100 km tunnel located at CERN
- New 16 T magnets (20 T for 80 km)
  - High challenging technologically
- Energy: 100 TeV
- One stage of overall FCC project
  - Full spectrum from e^+e^- to heavy ions

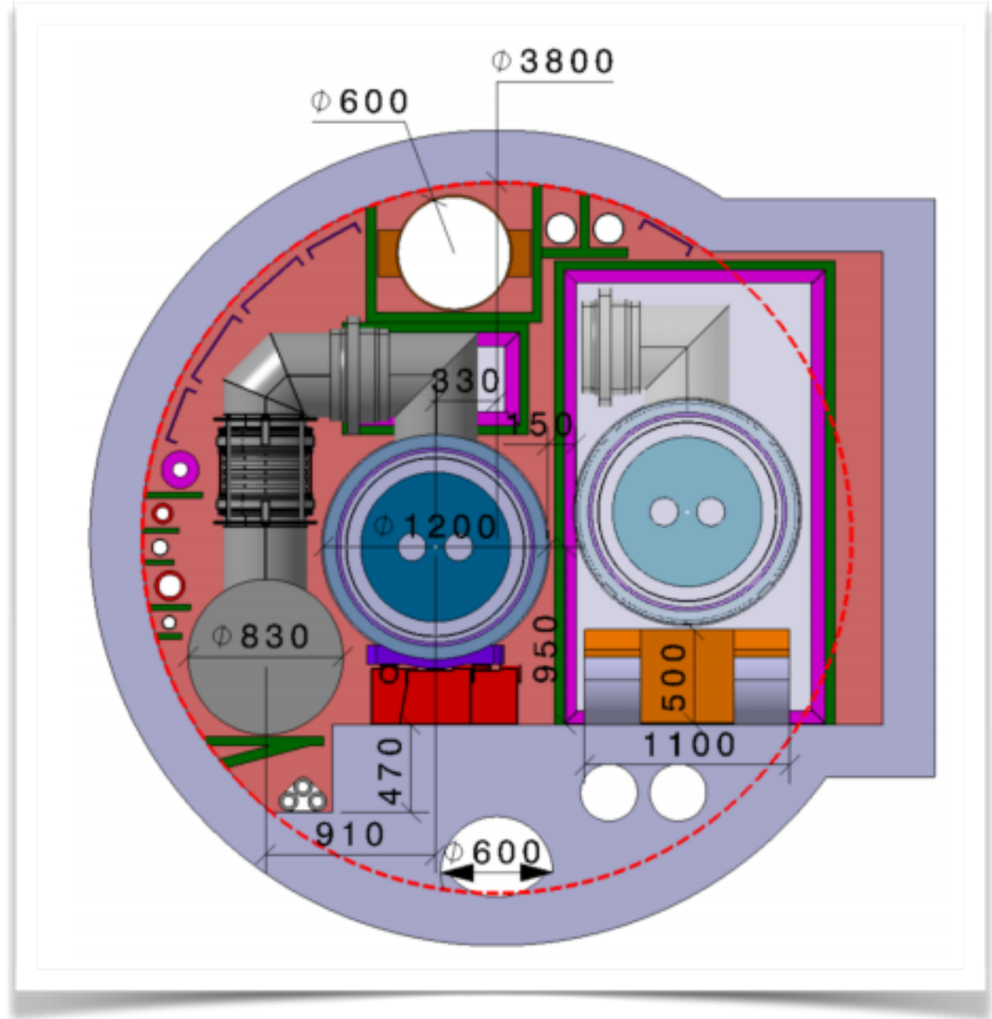


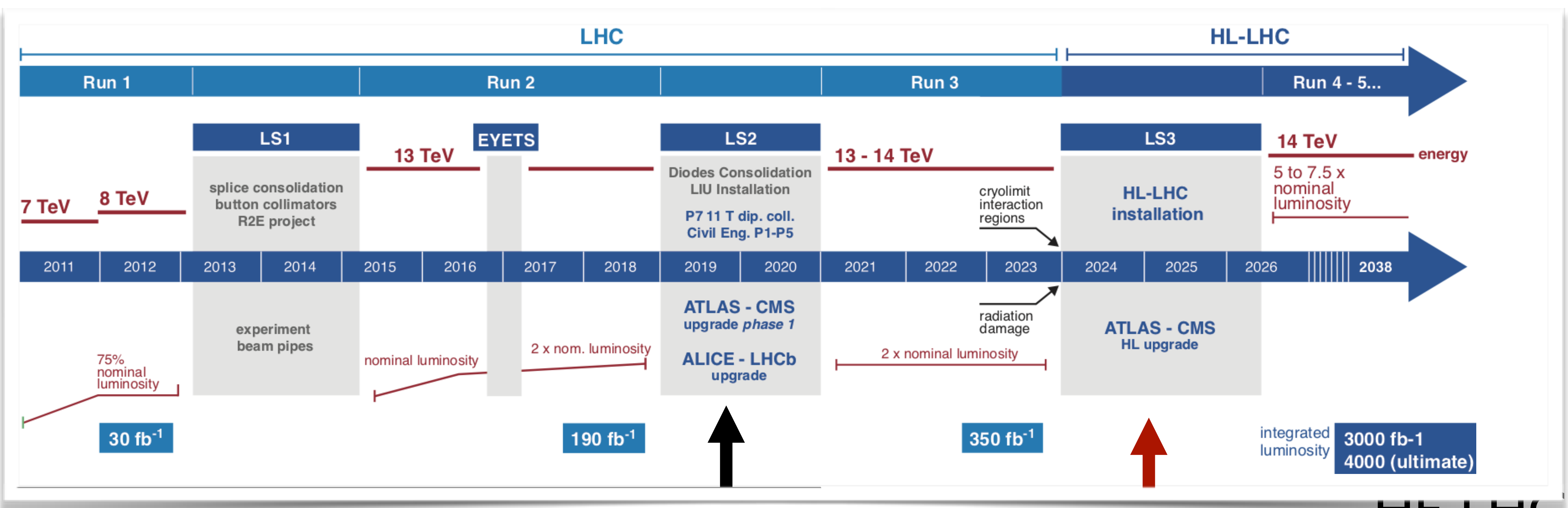
	√s	L /IP (cm⁻² s⁻¹)	Int. L /IP(ab⁻¹)	Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top	230 x10^{34} 28 8.5 1.5	75 ab^{-1} 5 2.5 0.8	2 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV	5 x 10^{34} 30	2.5 ab^{-1} 15	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39 TeV	3 x 10^{29}	65 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

FCC-hh Submission to ES

HL-LHC/HE-LHC

- Existing LHC tune
- Reuse the existing LHC tunnel
- Increase the magnetic field by installing the 16 T magnets from the FCC-hh
  - ➡Energy increases from 14 to 27 TeV
- Factor of 3 increase in luminosity over HL-LHC: 10 ab^{-1}





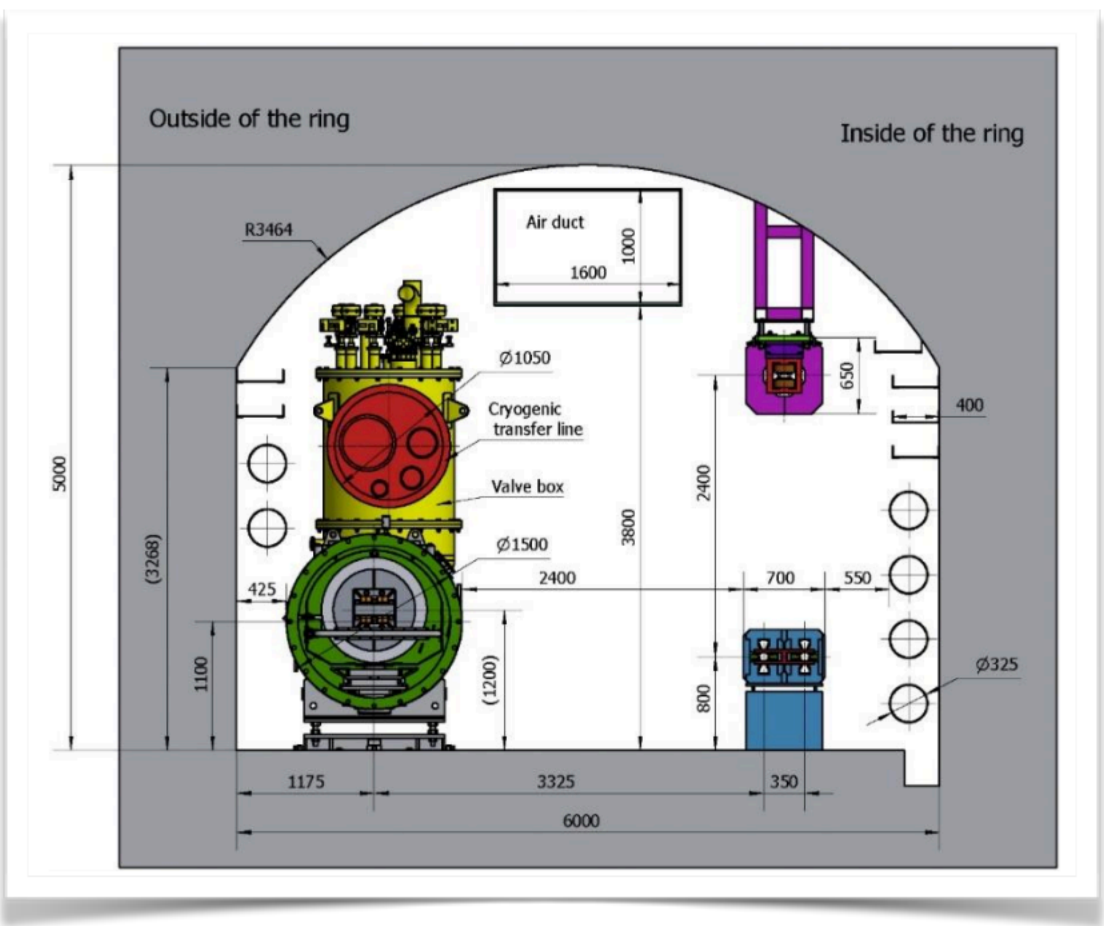
HE-LHC Submission

SppC

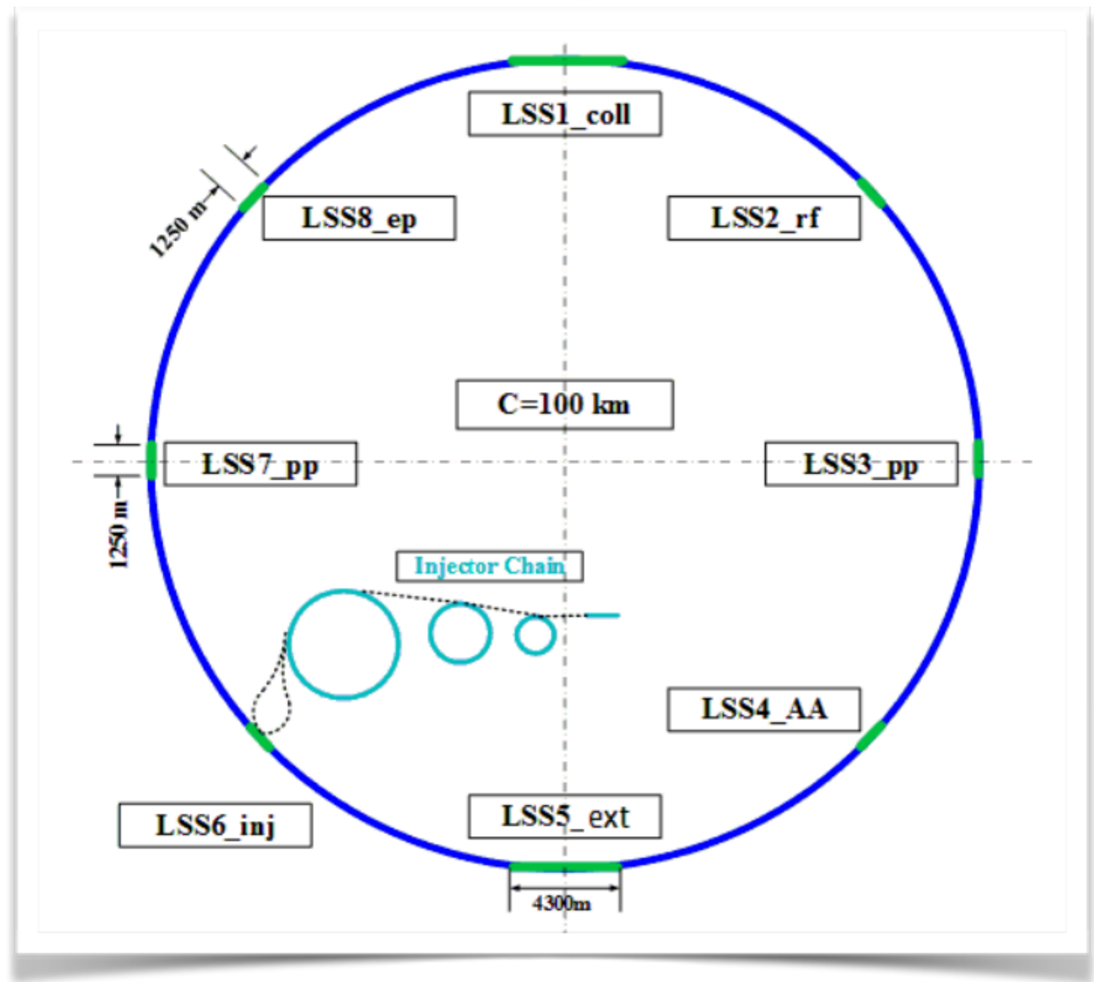
- New 100 km tunnel in China
- Magnets: initially 12 T; later 20 T
- Energy: 75 - 150 TeV
- Luminosity: 30 ab^{-1}

Physics case not yet mature, but can be expected to be the same as for FCC-hh for same energy/luminosity

Second step after CEPC

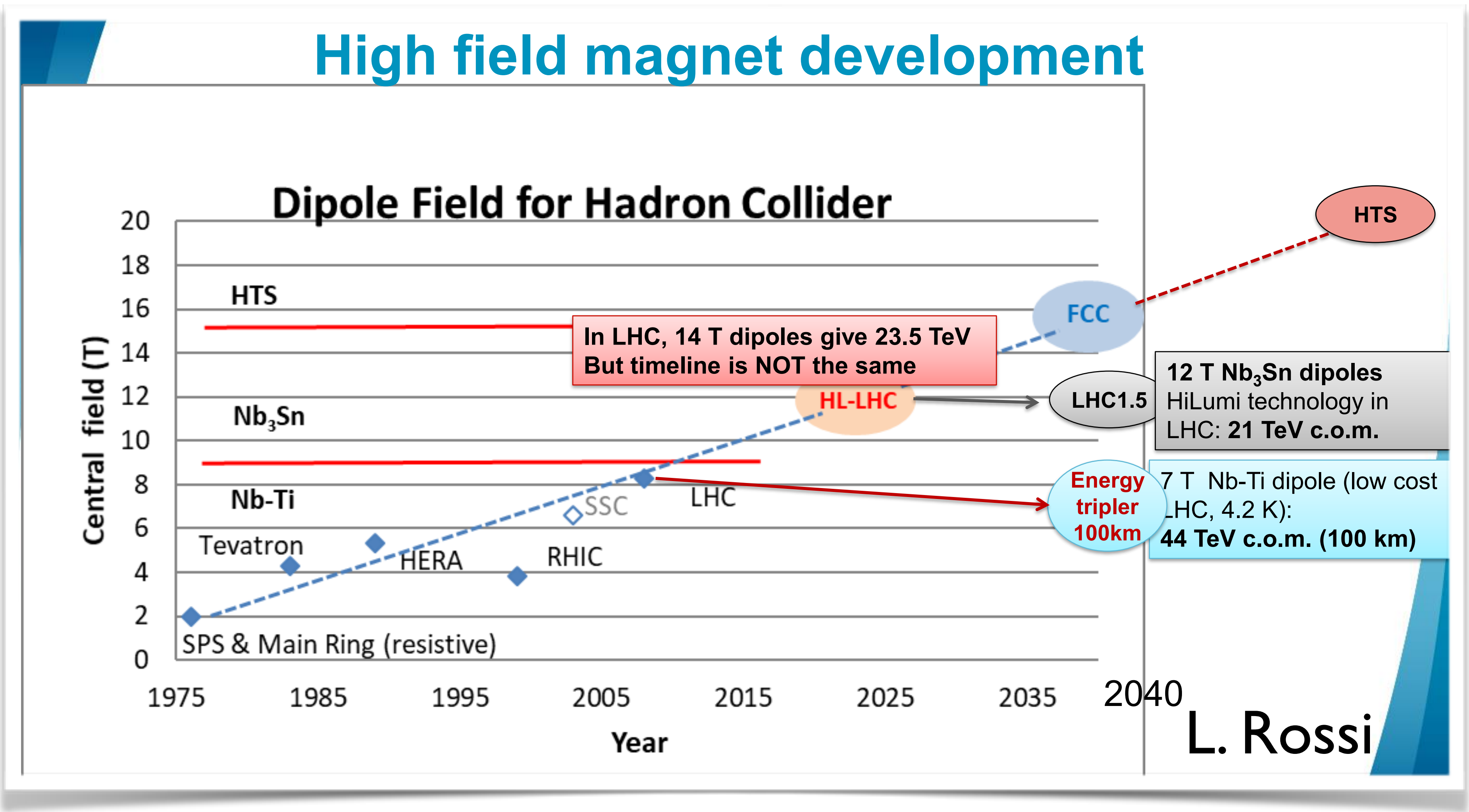


SppC Layout



SppC Submission to ES

Open Question: High field magnets



Personal (A. Yamamoto) View on Relative Timelines

Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Hadron Collider (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction			Operation		Upgrade
12~14T Nb_3Sn	Short-model R&D		Proto/Pre-series	Construction		Operation	
14~16T Nb_3Sn		Short-model R&D		Prototype/Pre-series		Construction	

Note: LHC experience: NbTi (10 T) R&D started in 1980's --> (8.3 T) Production started in late 1990's, in ~ 15 years

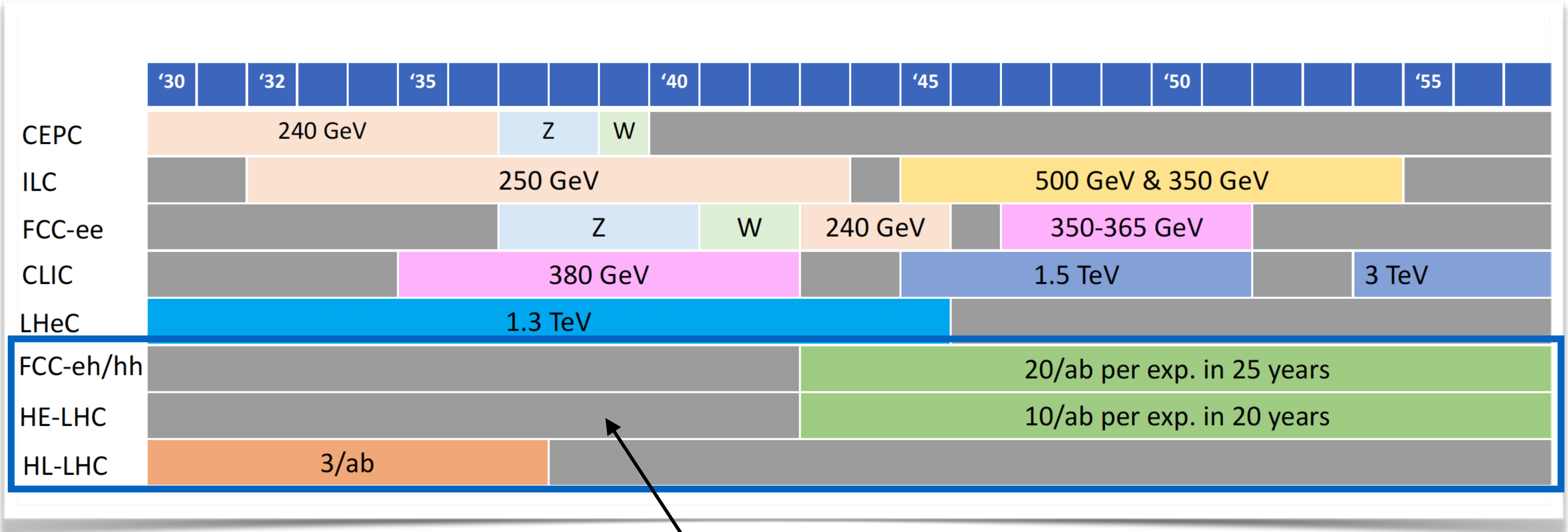
hadron collider schedule depends on magnet R&D

FCC-hh inputs

FCC-hh	
$\delta\mu_{ggF,4\mu}$	0.019
$\delta\mu_{ggF,\gamma\gamma}$	0.015
$\delta\mu_{ggF,Z\gamma}$	0.016
$\delta\mu_{ggF,\mu\mu}$	0.012
$\delta(\mathrm{BR}_{\mu\mu}/\mathrm{BR}_{4\mu})$	0.013
$\delta(\mathrm{BR}_{\gamma\gamma}/\mathrm{BR}_{2e2\mu})$	0.008
$\delta(\mathrm{BR}_{\gamma\gamma}/\mathrm{BR}_{\mu\mu})$	0.014
$\delta(\mathrm{BR}_{\mu\mu\gamma}/\mathrm{BR}_{\gamma\gamma})$	0.018
$\delta(\sigma^{bb}_{ttH}/\sigma^{bb}_{ttZ})$	0.019
Invisible decays	
$\mathrm{BR}_{\mathrm{inv}}$	<0.00013
Direct constraint on Higgs self-interaction	
$\delta\kappa_3$	0.05

FCC-hh (Extra inputs used in κ fits)	
$\delta(\sigma^{H\to\gamma\gamma}_{WH}/\sigma^{Z\to e^+e^-}_{WZ})$	0.014
$\delta(\sigma^{H\to\tau\tau}_{WH}/\sigma^{Z\to\tau\tau}_{WZ})$	0.016
$\delta(\sigma^{H\to bb}_{WH}/\sigma^{Z\to bb}_{WZ})$	0.011
$\delta(\sigma^{H\to WW}_{WH}/\sigma^{H\to\gamma\gamma}_{WH})$	0.015

Timescale and cost for Hadron Colliders



start date driven by magnet R&D

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

tunnel cost